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PROGRAMME

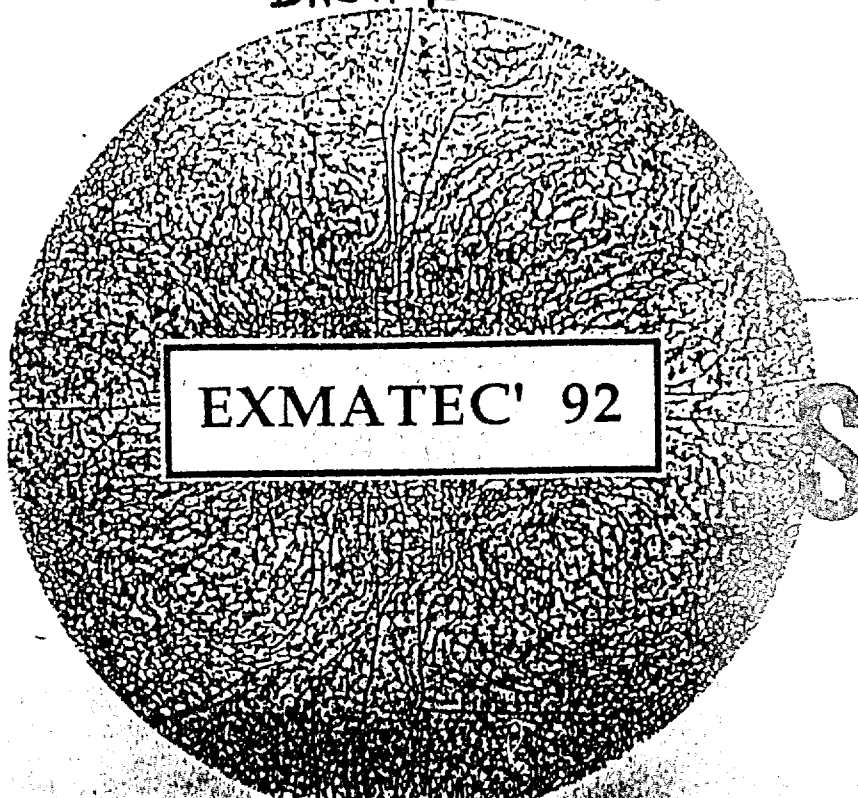
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ABSTRACTS

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EXMATEC' 92

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A

1st Workshop on

EXPERT EVALUATION AND CONTROL
OF COMPOUND SEMICONDUCTOR
MATERIALS AND TECHNOLOGIES

ECOLE CENTRALE DE LYON, FRANCE

19th to 22nd May 1992

This document has been approved
for public release and sale; its
distribution is unlimited.

CHAIRMAN:

S.K. KRAWCZYK

92-22565



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Laboratoire d'Electronique (UA CNRS)
36, av. G. de Collongue
69131 ECULLY Cedex, FRANCE
Tel: (33) 78 33 81 27 ext. 45 64 Fax: (33) 78 43 35 93

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FOREWORD

I am very pleased to welcome you to the 1st Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies (EXMATEC'92) at Ecole Centrale de Lyon (Ecully, France, 19th to 22nd May, 1992).

EXMATEC'92 starts a new series of workshops which are aimed at bringing together researchers involved in process development, material characterization, physics and the fabrication of compound semiconductor devices. The prime objective of the workshop is to strengthen the capability of compound semiconductor technologies to manufacture advanced devices with improved reproducibility, better reliability and lower cost.

Device structures become more and more complex and their dimensions decrease. Previously unknown and unexploited physical phenomena become of prime importance. The optimization and industrial exploitation of new devices demand a deep understanding of material properties in new device structures. Furthermore, innovative concepts are required for expert evaluation and control of still developing technologies.

In this context, the EXMATEC series will constitute a major forum for discussing material properties and their characterization in relation to advanced compound semiconductor devices.

For this first meeting of EXMATEC we have received an abundance of excellent quality abstracts originating from 15 different countries. Each abstract was submitted to three reviewers and final decisions were taken at the EXMATEC Steering and Scientific Committee Meeting held at Ecole Centrale de Lyon on 19 March 1992. About 100 oral and poster presentations have been retained. However, the success of the meeting will also depend on strong interactions between attendees through active participation. Even if you are not presenting an oral or poster contribution, you will still have the possibility to actively participate in the round tables as well as in informal discussions. Your experience will help others and, I am sure, you will take away some new ideas from EXMATEC.

The need for this type of meeting is already clear. The EXMATEC Steering Committee is now entertaining proposals for EXMATEC'94. All interested parties should contact me as soon as possible. The new chairman will be free to constitute fresh scientific and organizing committees. The present EXMATEC'92 Scientific and Steering Committee will become a steering body for the future meetings giving advice and scientific support to successive organizers.

With regard to location, "La Region Lyonnaise" is one of the most attractive historic areas in Europe. An interesting social programme has been arranged to help delegates and accompanying persons to enjoy the culture and style of life of Lyon, Beaujolais and Burgundy.

Finally, it remains for me to thank all who have helped me to transform a simple idea into a reality within just 6 months.

I thank all of those organizations and institutions who are actively supporting the workshop.

I would also like to express my gratitude to the EXMATEC Steering and Scientific Committee as well as to the Organizing Committee for all their hard work.

Many thanks also to the invited speakers, session chairmen, contributing authors and all of the attendees.

I have great pleasure in welcoming you to EXMATEC'92.

S. Krawczyk

S.K. KRAWCZYK
EXMATEC Chairman

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EXMATEC SCIENTIFIC & STEERING COMMITTEE

S.K. KRAWCZYK (Chairman), CNRS/ECL Ecully, France
W.T. ANDERSON, NRL, Washington DC, USA
R. BLUNT, Epitaxial Product International, UK
M. BONNET, Thomson CSF/TCM, France
J. DEEN, Simon Fraser University, Burnaby, Canada
P.N. FAVENNEC, CNET Lannion, France
J.P. FILLARD, Univ. Montpellier, France
H.L. HARTNAGEL, Technische Hochschule Darmstadt, FRG
H. HASEGAWA, Hokkaido University, Sapporo, Japan
A. HUBER, Thomson LCR, France
W. JANTZ, Fraunhofer - IAF, FRG
D. LECROSNIER, CNET Lannion, France
D. LILE, Colorado State University, Fort Collins, USA
S. MAHAJAN, Carnegie Mellon University, USA
S. MIYAZAWA, NTT LSI Laboratories, Atsugi, Japan
T. OGAWA, Gakushuin University, Tokyo, Japan
A. OZEKI, Fujitsu Laboratories Ltd, Atsugi, Japan
D. PAVLIDIS, The University of Michigan, Ann Arbor, USA
A. SCAVENNEC, CNET Bagneux, France
J.G. SWANSON, King's College London, UK
R. TRIBOULET, CNRS/LPSB Meudon, France
M. VAN ROSSUM, IMEC, Haverlee, Belgium
W. WETTLING, Fraunhofer - ISE, Freiburg, FRG
J. WEYHER, MASPEC, Parma, Italy

ORGANIZING COMMITTEE

S.K. KRAWCZYK (Chairman), CNRS/ECL Ecully, France
P. ANDREO, ECL, Ecully, France
P. BERGER, CNRS, Lyon, France
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N. RICHARDONE, ECL, Ecully, France
P. ROJO - ROMEO, ECL, Ecully, France
K. SCHOHE, SCANTEK, Ecully, France

SUPPORTING ORGANIZATIONS

Centre National de la Recherche Scientifique (CNRS)
Centre National d'Etudes des Télécommunication (CNET)
Commission of the European Communities
Ecole Centrale de Lyon (ECL)
European Research Office of the United States Army
Mairie d'Ecully
Ministère de la Défense - Direction des Recherches, Etudes et Techniques (DRET)
Office of the United States Naval Research European Office
Société des Electriciens et des Electroniciens (SEE)

1 - REGISTRATION

All participants must be registered for EXMATEC' 92.

A copy of the registration form was attached to the "Advance Programme and Registration Information". Additional copies are available at the registration desk.

The registrations fees include : access to all sessions and exhibitions, Workshop Handbook, Workshop Proceedings, bus transportation, refreshments, welcoming reception (19 May), lunches (20, 21 and 22 May), evening excursion to "Vieux Lyon" (20 May), workshop excursion and workshop dinner in Beaujolais (21 May afternoon and evening). Hotel accommodation is not included. The Workshop Handbook and the Workshop Proceedings are not supplied to accompanying persons.

Payments should be made in French Francs net of charges. The conference organizers are not able to accept credit card payments.

2 - HOTEL RESERVATION

A number of rooms at a special conference rate have been reserved in three different hotels. A reservation form for each was enclosed with the "Advance Programme and Registration Information".

In case of any problems, please contact the registration desk.

3 - WORKSHOP LOCATION

The Workshop is being held at Ecole Centrale de Lyon (ECL), which is one of the French "Grandes Ecoles" and is an important center of basic and applied research. ECL is located in Ecully, a beautiful residential town west of Lyon (about 10 km from the center).

Lyon is located 450 km south of Paris, about 100 km west from the Alps and about 300 km north of the Mediterranean Sea. Lyon, the second city of France, is easily accessible by plane (direct flights from all major European cities and from New York) and by train (the TGV ride from Paris takes 2 hours). The city has a very rich Gallic and Roman history and, in addition, is acknowledged as the capital of French Gastronomy.

4 - CONFERENCE VENUE

The arrival of conference attendees is expected on 19 May 1992 (Tuesday) afternoon at the Workshop Area at Ecole Centrale de Lyon.

The registration desk will be open during the following hours :

| | | |
|------------|-------------|----------------------|
| Tuesday, | 19 May 1992 | from 15:00 to 21:00. |
| Wednesday, | 20 May 1992 | from 8:00 to 17:00 |
| Thursday, | 21 May 1992 | from 8:00 to 12:00 |
| Friday, | 22 May 1992 | from 8:00 to 16:00 |

On 19 May 1992, the participants will have an opportunity for informal discussions, visiting an industrial exhibition associated with the EXMATEC Workshop, visiting the Laboratoire d'Electronique (UA CNRS) at Ecole Centrale de Lyon. Also, posters should be installed on the afternoon of 19 May. Soft drinks, cakes and coffee will be available without interruption. An informal welcoming cocktail (18:00 -19:30) followed by the welcoming reception (19:30 - 22:00) will be held 19 May 1992 in the marquee adjoining the Conference Area.

5- INFORMATION FOR ACTIVE PARTICIPANTS

Oral presentations :

For oral presentations overhead and slide projectors will be available. The allocated time is as follows :

- Invited lectures : 30 minutes, including 5 minutes for discussion
- Contributed papers/oral : 15 minutes, including 3 minutes for discussion

The allocated time must be strictly respected !

Poster presentations :

- Allocated space : 1 m x 1.50 m (maximum width and height, respectively)
- Support for posters : posters must be fixed with an adhesive tape
- The poster session is indicated in the programme
- Posters will be displayed throughout the entire conference period
- Poster installation : 19 May 1992 afternoon
- Poster dismounting : 22 May 1992 afternoon

Round table discussions :

Three round table discussions will be held in parallel on 22 May 1992 (10:00 - 11:30). The topics and subtopics are indicated in the programme. All participants are encouraged to prepare one or two transparencies with the material supporting the discussion or with questions to the attendees. A list of active participants in round table discussions together with the titles of their contributions will be published in the Workshop Handbook.

In order to help the discussion leaders in the preparation of round tables, please answer the questions in the document "INFORMATION FOR THE ORGANISERS" provided to all participants at the registration desk.

6- WORKSHOP PROCEEDINGS

The papers presented at the Workshop will be published in a special issue of Materials Science and Engineering B: Solid State Materials for Advanced Technology. For this purpose, the papers will be reviewed and only the accepted papers will be published. The papers will be type set. The authors will receive 25 reprints free of cost. All registered participants will receive a free copy of the special issue, we plan to publish this in January 1993. The manuscripts must reach the Chairman by 15 June 1992.

7- ADDITIONAL INFORMATION

Coffee breaks

Coffee, cakes and soft drinks will be served during the breaks in the Conference Area.

Lunches

Lunches will be served in the marquee adjoining the Conference Area.

Message service

A message service will be provided during registration hours. Messages may be left by telephone +(33) 78 33 52 76 or by fax +(33) 78 43 35 93 with reference to EXMATEC'92. The received messages will be posted on a display board near the registration desk. In addition, there will be two pay-phones in the Conference Area, which will be capable of receiving in-coming calls.

8 - TECHNICAL EXHIBITION

In addition to the Workshop programme, an industrial exhibition will be held in two rooms adjacent to the conference area.

EXHIBITORS :

ADDAX Technology
ZI de Percevalière
BP 1
38170 SEYSSINET-PARIZET

BIORAD S. A.
Division Microscience
94-96, avenue Victor Hugo
94200 IVRY/SEINE

CRISMATEC-INPACT
Usine de Plombière
73600 MOUTIERS

JIPELEC
95, rue Général Mangin
38100 GRENOBLE

LEICA SARL
Division MSI
86, avenue du 18 juin 1940
92563 RUEIL-MALMAISON Cédex

SCANTEK
9, Chemin du Petit Bois
69130 ECULLY

SCIENCE ET SURFACE S. A.
La Combe de Charbonnières
78, Route de Paris
69200 CHARBONNIERES

9- SUMMARY OF SOCIAL ACTIVITIES

Tuesday, 19 May 1992

18:00 - 19:30 Welcoming cocktail
19:30 - 22:00 Welcoming reception
Both will be held in the marquee adjoining the Conference Area

Wednesday, 20 May 1992

18:45 - 19:45 Cocktail offered by the Community of Ecully and the Ecole Centrale de Lyon (in the marquee)
20:00 Departure of buses (from the Conference Area) for the Evening Excursion to "Vieux Lyon" (with English speaking guides)
21:30 - 24:00 Participants will be free to see the city and to choose a restaurant
24:00 Departure of buses from Place St. Paul in "Vieux Lyon" for the hotels

Thursday, 21 May 1992

Workshop excursion and banquet in Beaujolais (14:00 to 24:00)

14:00 Departure of buses from the Conference Area
- visit to the home of Ampère and the Museum of Electricity
- visit to two Beaujolais vineyards with wine testing at each
- banquet at the Chateau des Loges at Le Péréon in Beaujolais
24:00 Departure of buses from the Chateau for the hotels

10 - ACCOMPANYING PERSONS

A full day tour including visits to Burgundian castles and cathedrals will be arranged on Wednesday, 20 May 1992 (8:30 - 18:00). See the enclosed description and indicate your interest to the registration desk. We will also provide advice and help to those wanting to visit other tourist attractions in and around Lyon.

ACCOMPANYING PERSONS TOUR ON WEDNESDAY, 20 MAY 1992

"Southern Burgundy - land of art and good living"

Leaving your hotel at 8:30 a.m., a one hour highway drive will take you to Tournus, Southern Burgundy, a charming little town lying by the river Saône.

In Tournus you will visit the 10th Century abbey, a true masterpiece of early Romanesque architecture.

Then, following a quiet and picturesque road running by small castles and villages, you will discover some of the most beautiful scenery of the Burgundian countryside, giving you a real feeling of "the true flavour of France".

You will wander through the mediaeval village of Brancion, overlooking the Grosne valley, admire the church of Chapaize, another beautiful example of Romanesque architecture, and have a regional lunch in a small country inn offering an exceptional panorama of the region.

After lunch, we will take you to Cluny to visit the site and vestiges of the famous abbey, home of the former Clunisian order which had a predominant influence over the Western world between the Middle-Age and the Renaissance. The afternoon will also include a visit to Taizé, the famous place of pilgrimage.

On your way back to Lyon, before entering the highway, you will drive through the vineyards of Pouilly-Fuissé, among the most spectacular in the region, passing by majestic 15th Century castles.

Arriving at your hotel at around 5:00 pm.

PRICES :

| | |
|-----------------------|-----------------|
| Based on 10 persons : | 550 FF / person |
| Based on 15 persons : | 475 FF / person |
| Based on 20 persons : | 400 FF / person |

The prices comprise :

- Bus transport
- An English speaking cultural guide for the day
- Entry to the historic buildings that will be visited
- Lunch with wine and coffee included
- A document describing the region in English for each participant

PLANARY SESSIONS

WEDNESDAY, MAY 20, 1992

8:30 - 8:45 Opening Session

**Session n° 1 : Performance and reliability of micro-optoelectronic devices
in connection with material properties and process conditions - I
(8:45 - 10:15)**

Chairman : D. Lile, Colorado State University, Fort Collins, USA

8:45 - 9:15 INVITED LECTURE

**"Material Related Issues and Their Characterization in View of III-V
Heterojunction Device Optimization"
D. Pavlidis, The University of Michigan, Ann Arbor, USA**

9:15 - 9:30

**Material Problems for the Development of InGaAs/InAlAs HEMTs Technology.
K. Zekentes¹⁾, G. Halkias¹⁾, A. Dimoulas¹⁾, N. Kornilos¹⁾, A. Tabata²⁾, T. Benyattou²⁾,
G. Guillot²⁾, J.R. Morante³⁾, F. Peiro³⁾, A. Cornet³⁾, A. Georgaklias⁴⁾, A. Christou⁴⁾,
¹⁾ Foundation for Research and Technology-Hellas, Crete, Greece, ²⁾ INSA de Lyon,
Villeurbanne, France, ³⁾ Universitat de Barcelona, Barcelona, Spain, ⁴⁾ University of
Maryland, College Park, MD, USA.**

9:30 - 9:45

**Theoretical and Experimental Study of Failure Mechanisms in RF Reliability Life Tested
HEMTs. W.T. Anderson¹⁾, K.A. Christianson¹⁾, C. Moglestue²⁾, ¹⁾ Naval Research
Laboratory, Washington, DC, USA, ²⁾ Fraunhofer-IAF, Freiburg, Germany.**

9:45 - 10:00

**A Study of Detrimental Transient Effects in GaAs HEMTs. J.M. Dumas¹⁾, P. Audren²⁾,
M.P. Favennec²⁾, S. Mottet¹⁾, D. Lecrosnier¹⁾, M. Gauneau¹⁾, ¹⁾ CNET, Lannion, France,
²⁾ Institut Universitaire de Technologie, Lannion, France.**

10:00 - 10:15

**Relating μ -Wave Mapped Data to Physical Parameters for MODFETs. J. Braunstein,
P.-J. Tasker, M. Schlechtweg, A. Hülsmann, G. Kaufel, K. Köhler, Fraunhofer-IAF,
Freiburg, Germany.**

10:15 - 10:30 Coffee Break

WEDNESDAY, MAY 20, 1992

**Session n° 2 : Performance and reliability of micro-optoelectronic devices
in connection with material properties and process conditions - II
(10.30 - 12:00)**

Chairman : H.L. Hartnagel, THD, Darmstadt, Germany

10:30-11:00 INVITED LECTURE

"Material Related Reliability Aspects of III-V Optical Devices"
O. Ueda, Fujitsu Laboratories Ltd., Atsugi, Japan

11:00 - 11:15

A Possible Origin of Degradation Mechanisms in AlGaAs/GaAs Laser-Like Structures.
**B. Sieber¹⁾, J.L. Farvacque¹⁾, J. Wang²⁾, J.W. Steeds²⁾, ¹⁾ Université des Sciences et
Technologies de Lille, Villeneuve d'Ascq, France, ²⁾ University of Bristol, Bristol, U.K.**

11:15 - 11:30

Thermal Stability of Pseudomorphic HEMTs. A.A. Rezazadeh¹⁾, N.L. Saunders²⁾,
D.V. Morgan²⁾, H. Thomas²⁾, R.S. Smith³⁾, P. Kirby³⁾, ¹⁾ King's College, London,
U.K., ²⁾ University of Wales, Cardiff, UK, ³⁾ GEC Hirst Research Center, Wembley, UK.

11:30 - 11:45

Detailed Process Analysis for Controlling the Yield of GaAs MMIC's Technology
J.L. Pinsard, A. Kalfane, Thomson Composants Microondes, Orsay, France.

11:45 - 12:00

**Spatially Resolved Photoluminescence Techniques Applied to the Control of InGaAsP/ InP
Laser Processing.** A. Guichardon¹⁾, M. Boulou¹⁾, A. Duick²⁾, J.L. Gentner²⁾, ¹⁾ Alcatel
Alsthom Recherche, Marcoussis, France, ²⁾ Alcatel CIT/OCD, Marcoussis, France

WEDNESDAY, MAY 20, 1992

Session n° 3 : Growth and characterization of epitaxial structures
(14 :00- 16:45)

Chairman : G. Salmer, Université des Sciences et Technologies de Lille,
Villeneuve d'Ascq, France.

14:00 - 14:30 INVITED LECTURE

"Atomic Ordering and Phase Separation in Compound Semiconductors and their Effect on Device Behavior"

S. Mahajan, Carnegie Mellon University, Pittsburgh, USA

14:30 - 15:00 INVITED LECTURE

"Improved Device Quality by Strained Layer Epitaxy"

H. Beneking, RWTH Aachen, Germany

15:00 - 15:15

II-VI Semiconductor Strained Heterostructures : A Structural Review. G. Feuillet, CENG,
Grenoble, France.

15:15 - 15:30

Interface Properties of Strained InGaAs/InP Quantum Wells Grown by LP-MOVPE.
R. Schwedler¹⁾, B. Gallmann¹⁾, K. Wolter¹⁾, A. Kohl¹⁾, K. Leo¹⁾, H. Kurz¹⁾,
F.H. Baumann²⁾, ¹⁾ RWTH Aachen, Germany, ²⁾ AT&T Bell Laboratories, Holmdel, NJ,
USA.

15:30 - 15:45

Raman Scattering in In_xGa_{1-x}As/GaAs Superlattices Grown by MBE. M. Constant, N.
Matrullo, A. Lorriaux, R. Fauquembergue, Y. Druelle, J. Di Persio, Université des
Sciences et Techniques de Lille , Villeneuve d'Ascq, France.

15:45 - 16:00

Non-Destructive Approaches of Interdiffusion Phenomena Across InGaAs/InGaP
Interfaces : Photoluminescence versus Raman. H. Peyre¹⁾, S. Juillaguet¹⁾, E. Massone¹⁾,
J. Camassel¹⁾, F. Alsina²⁾, J. Pascual²⁾, R.W. Glew³⁾, ¹⁾ Université de Montpellier II,
Montpellier, France, ²⁾ Dept. Fisica, Bellaterra, Spain, ³⁾ BNR-EUROPE Ltd., Harlow,
UK.

16:00- 16:15

Determination of Carrier Densities in AlGaAs/GaAs Heterojunction and Superlattice
Structures by Photoluminescence Spectroscopy. Z.H. Lu, E. Mao, B.W. Kim, A. Majerfeld,
University of Colorado, Boulder, CO, USA.

16:15 - 16:30

Selective Growth of GaAs and GaAlAs by Cl-Assisted OMVPE at Atmospheric Pressure.
R. Azoulay, L. Dugrand, A. Izrael, E.V.K. Rao, R. Mellet, A.M. Pougnet, CNET,
Bagneux, France.

16:30 - 16:45

Photoluminescence Microscopy Investigation of Lattice Defects in Heterostructures Grown
by MOVPE and MBE. Z.M. Wang, M. Baeumler, K. Bachem, E.C. Larkins, J.D. Ralston,
W. Jantz, Fraunhofer-IAF, Freiburg, Germany.

16:45 - 17:00 Coffee Break

17:00 - 18:30 POSTER SESSION

THURSDAY, MAY 21, 1992

Session n° 4 : Growth and characterization of compound semiconductors (8:30 -10:45)

Chairman : A. Winnacker, University of Erlangen, Germany.

8:30 - 9:00 INVITED LECTURE

"Crystallographic and Chemical Inhomogeneities in Compound Semiconductor Substrates and their Relevance to Device Performance"
J. Weyher, MASPEC, Parma, Italy

9:00 - 9:30 INVITED LECTURE

"Two Direct Analytical Methods for Semiconductor Materials Assessment"
A. Huber and C. Grattepain, Thomson LCR, Orsay, France

9:30 - 9:45

Photoluminescence and Photoacoustic Investigation of Residual Defects in Semi-Insulating LEC GaAs. O. Ka¹⁾, O. Oda²⁾, Y. Makita¹⁾, A. Yamada¹⁾,
¹⁾ Electrotechnical Laboratory, Tsukuba, Japan, ²⁾ Nippon Mining Co., Tsukuba, Japan.

9:45 - 10:00

SIRM and TEM Studies of Inhomogeneities in S-Doped InP. N.Y. Jin¹⁾, G.R. Booker¹⁾, I.R. Grant²⁾, ¹⁾ Oxford University, Oxford, UK, ²⁾ MCP Wafer Technology Limited, Milton Keynes, UK

10:00 - 10:15

On the Distribution of Fe in Semi-Insulating InP. R. Treichler¹⁾, J. Völkl²⁾, Th. Vetter²⁾, G. Wittmann²⁾, A. Winnacker³⁾, ¹⁾ Siemens Corporate Research and Development, Munchen, Germany, ²⁾ Siemens Corporate Research and Development, Erlangen, Germany, ³⁾ University of Erlangen, Erlangen, Germany.

10:15 - 10:30

Recent Advance in the Assessment of GaAs Substrate Quality by Scanning Photoluminescence. K. Schohe¹⁾, F. Krafft²⁾, C. Kingelhöfer²⁾, M. Garrigues¹⁾, S.K. Krawczyk²⁾, J. Weyher³⁾, ¹⁾ SCANTEK, Ecully, France, ²⁾ Ecole Centrale de Lyon, Ecully, France, ³⁾ MASPEC, Parma, Italy.

10:30 - 10:45

Electrical Properties of Thermally Annealed Fe-Doped Semi-Insulating InP. A. Kalboussi¹⁾, G. Marrakchi¹⁾, G. Guillot¹⁾, K. Kainosho²⁾, O. Oda²⁾, ¹⁾ INSA de Lyon, Villeurbanne, France, ²⁾ Nippon Mining Company, Saitama, Japan.

10:45 - 11:00 Coffee Break

Session n° 5 : New frontiers (11:00 -12:00)

Chairman : J.P. Fillard, Université de Montpellier II, France.

11:00 - 11:30 INVITED LECTURE

"From Micro- to Nanoelectronics : New Technology Requirements"
M. Van Rossum, IMEC, Heverlee, Belgium

11:30 -12:00 INVITED LECTURE

"Evaluation of III-V Epitaxial Layers Grown by Atomic Layer Epitaxy"
M. Ozeki and A. Shibatomi, Fujitsu Laboratories Ltd., Atsugi, Japan

12:00 - 14:00 LUNCH

14:00 - 24:00 WORKSHOP EXCURSION AND BANQUET

FRIDAY, MAY 22, 1992

Session n° 6 :Towards technology improvements (8:45 - 9:45)

Chairman : P. Viktorovitch, Ecole Centrale de Lyon, Ecully, France

8:45 - 9:15 INVITED LECTURE

"Concepts of Ultra-Stable Metal Contacts and their Evaluation"

H.L. Hartnagel, THD, Darmstadt, Germany

9:15 - 9:45 INVITED LECTURE

"UVCVD Dielectric Deposition for InP-Based Optoelectronic Devices"

G. Post, Y. Le Bellego, J.L. Courant, A. Scavennec, CNET Bagneux, France

9:45 - 10:00 Break

10.00 - 11.30 ROUND TABLE DISCUSSIONS

1) State of the art of compound semiconductor substrates and topical problems :

- crystal growth and post-growth treatments,
- structural/chemical interactions,
- surface preparation,
- application related substrate specification.

Discussion leaders :

R. Fornari, MASPEC, Parma, Italy

A. Huber, Thomson LCR, Orsay, France

J. Weyher, MASPEC, Parma, Italy

2) Growth and characterization of advanced epitaxial structures :

- lattice mismatched epitaxy,
- growth, stability and physical properties of strained heterostructures,
- selective epitaxy,
- nanometric structures,
- non-destructive analytical techniques for complex multilayer structures.

Discussion leaders :

R. Azoulay, CNET, Bagneux, France

R. Blunt, Epitaxial Product International, Cardiff, UK

W. Jantz, Fraunhofer - IAF, Freiburg, Germany

M. Mariette, CENG, Grenoble, France

3) Process induced defects in compound semiconductor structures :

- epitaxial regrowth,
- implantation,
- annealings,
- plasma etching and treatments,
- dielectric deposition,
- *in situ* characterization techniques.

Discussion leaders :

P.N. Favennec, CNET, Lannion, France

H.L. Hartnagel, THD, Darmstadt, Germany

D. Lile, Colorado State University, Fort Collins, USA

11:30 - 13:30 LUNCH

FRIDAY, MAY 22, 1992

**Session n° 7 : Advanced material and process characterization techniques
(13.30 - 16:00)**

Chairman : C. Frigeri, MASPEC, Parma, Italy

13:30 - 13:45

Stability of GaAs MESFET's Gate Contact Studies by High Resolution TEM. N. Labat¹⁾, Y. Danto¹⁾, B. Plano¹⁾, M. Chambon¹⁾, J.M. Dumas²⁾, ¹⁾ Université de Bordeaux I, Talence, France, ²⁾ CNET, Lannion, France.

13:45 - 14:00

Investigation of Photoluminescence Mapping and Transients in AlGaAs/GaAs Heteroface Solar Cells. A. Ehrhardt, W. Wettling, S. Cardona, Fraunhofer-ISE, Freiburg, Germany.

14:00 - 14:15

Photoluminescence Surface State Spectroscopy for In-Situ Semiconductor Surface and Processing Characterization. H. Hasegawa, T. Saitoh, K. Numata, T. Sawada, Hokkaido University, Sapporo, Japan.

14:15 - 14:30

Studies of GaAs Surfaces by Scanning Tunneling Induced Photon Emission. M. Bischoff, C. Sprössler, H. Pagnia, R. Richter, J. Horn, H.L. Hartnagel, Technical University of Darmstadt, Darmstadt, Germany.

14:30 - 14:45

Gated Photoluminescence and Raman Spectroscopy Analysis of InP Interfaces. D.L. Lile, M. Ochiai, R. Iyer, Colorado State University, Fort Collins, USA.

14:45 - 15:00

Opto-Electronic Modulation Spectroscopy (OEMS) - a New Tool for Device Investigations. M. Di Marco, Q. Wang, J.G. Swanson, King's College, London, U.K.

15:00 - 15:15

A Study of Light Intensities Scattered from Defects in an In-doped LEC GaAs Crystals as a Function of Wavelength and Intensity of Bias Light Superposed on the Defects. K. Sakai, R. Hashimoto, T. Ogawa, Gakushuin University, Tokyo, Japan.

15:15 - 15:30

Optical NDT for Evaluation of Microprecipitates in Semiconductor Materials and Devices. J.P. Fillard, Université de Montpellier II, Montpellier, France.

15:30 - 15:45

Optical Characterization of Si Wafers for ULSI. T. Ogawa¹⁾, T. Lu²⁾, K. Toyoda²⁾, N. Nango³⁾, ¹⁾ Gakushuin University, Tokyo, Japan, ²⁾ Institut of Physical & Chemical Research, Saitama, Japan, ³⁾ Ratoc Systems Engineering Co., Tokyo, Japan.

15:45 - 16:00

The Effects of Probe Power Density on the Spatially Resolved Room Temperature Photoluminescence of Optoelectronic Epitaxial Structures. C.J.L. Moore, J. Hennessy, Waterloo Scientific Inc, Waterloo, Ontario, Canada.

16:00

END OF THE WORKSHOP

POSTER PRESENTATIONS

1- Be⁺ Ion Implantation in Ga(Al)Sb Layers. Radiation Damage. M. Perotin¹⁾, A. Perez²⁾, H. Luquet¹⁾, L. Gouskov¹⁾, A. Sabir¹⁾, ¹⁾ Université de Montpellier II, Montpellier, France, ²⁾ Université Cl. Bernard Lyon I, Villeurbanne, France.

2- Investigation of Electrically Active Defects in Plasma Etched GaAs. S. V. Koveshnikov, E.B. Yakimov, S.V. Dubonos, Russian Academy of Sciences, Moscow, Russia.

3- Mapping and Profiling of Diffusion Length and Depletion Region Width in GaAs Schottky Diodes. O. Kononchuk, E. Yakimov, Russian Academy of Sciences, Moscow, Russia.

8- Influence of the Substrate on the Diffusion Length and the Interface Recombination Velocity of GaAs Homostructures Detected by SEM/EBIC Experiments. F. Cleton, B. Sieber, J.L. Loriaux, Université des Sciences et Technologies de Lille, Villeneuve d'Ascq, France.

11- Defects and Uniformities in MOCVD HgCdTe and GaInAsSb Grown on GaAs Substrates. Peng Rui-wu, Wei Guang-yu, Ding Yong-ging, Chinese Academy of Sciences, Shanghai, P. R. China.

13- Ternary and Quaternary III-V Semiconductors Grown by HVPE. C. Pelosi¹⁾, G. Attolini¹⁾, C. Bocchi¹⁾, C. Frigeri¹⁾, A. Carnera²⁾, M.L. Favaro³⁾, D. Ajo³⁾, ¹⁾ MASPEC, Parma, Italy, ²⁾ Università di Padova, Padova, Italy, ³⁾ ICTR, Padova, Italy.

16- Generalized Analysis on the Photovoltage Decay Characteristic of Solar Cells. G. Sissoko¹⁾, M. L. Sow¹⁾, F. Pelanchon²⁾, M. Kane¹⁾, P. Mialhe²⁾, ¹⁾ U.C.A.D., Dakar, Sénégal, ²⁾ Université de Perpignan, Perpignan, France.

19- Influence of the Base P-Type Dopant (Be, Zn, C) on Mg Distributions in Mg-Implanted HBT Devices. V. Amarger, C. Dubon-Chevalier, B. Descouts, Y. Gao, CNET, Bagneux, France.

20- A Quasi Planar GaAlAs/GaAs HBT with All Ohmic Contact in Tungsten Made by Selective Area Chemical Beam Epitaxy. J. Zerguine, F. Alexandre, P. Launay. CNET, Bagneux, France.

21- Nitridation of Thermal SiO₂ Thin Films Studied by Auger Electron Spectroscopy. V. Roge¹⁾, A. Glachant²⁾, ¹⁾ CRMC2-CNRS- Luminy, Marseille, France, ²⁾ Université de Toulon et du Var, La Garde, France

22- Study of Defects in InP by DSL and LST. N. Tchandjou, E. Baudry, J.M. Lussert, Université de Montpellier II, Montpellier, France.

24- Physicochemical Characterization by Means of Infrared Absorption Spectroscopy of Si₃N₄ Thin Films Obtained from C.V.D. Assisted by In-Situ Electrical Discharge. R. Botton¹⁾, B. Balland¹⁾, J.C. Bureau¹⁾, A. Glachant²⁾, M. Lemiti¹⁾, ¹⁾ INSA de Lyon, Villeurbanne, France, ²⁾ Faculté des Sciences de Luminy, Marseille, France.

25- Application of DLTS for Monitoring Point Defects in III-V Semiconductors. P. Kaminski, Institute of Electronic Materials Technology, Warszawa, Poland.

26- Optical Thickness Mapping of Epitaxial Layers. M. Brandstädtner, G. Betz, Phoenixicon GmbH, Berlin, Germany.

27- Low Frequency Noise as a Characterization Tool in InP and GaAs-based Double Barrier Resonant Tunneling Diodes. J. Deen, Simon Fraser University, Burnaby, B. C., Canada.

28- Electrical Conduction in Two-Phase PbTe-Sb₂Te₃ Alloys. P.P. Sahay, M. Shamsuddin, R.S. Srivastava, Banaras Hindu University, Varanasi, India.

30- EBIC Microtomography of Microcracks in Silicon Plates. S.K. Likharev, V.P. Trifonenkov, V.V. Vybornov, Moscow State University, Moscow, Russia.

31- SPL Characterization of Iron Doped GSMBE InP Layers. H. L'Haridon, A. Le Corre, S. Salaün, D. Lecrosnier, A. Godefroy, M. Gauneau, CNET, Lannion, France.

35- Photoluminescence Characterization of Oxidized Schottky Diodes Obtained by Multipolar Plasma Oxidation of InP. A. Bath¹⁾, A. Ahaitouf¹⁾, B. Lepley¹⁾, M. Belmahi²⁾, M. Remy²⁾, S. Ravelet³⁾, ¹⁾ Université de Metz, Metz, France, ²⁾ Université de Nancy, Vandoeuvre-lès-Nancy, France, ³⁾ ESSTIN, Vandoeuvre-lès-Nancy, France.

36- Investigations of Ohmic Contact Systems with Diffusion Barriers on n-GaAs. E. Nebauer¹⁾, U. Merkel¹⁾, M. Mai¹⁾, P. Weissbrodt²⁾, ¹⁾ Ferdinand-Braun-Institut, Berlin, Germany, ²⁾ Jenoptik GmbH, Jena, Germany.

37- Photoluminescence Characterization of GaInAs/AlInAs HEMT Structures. A. Tabata¹⁾, T. Benyattou¹⁾, G. Guillot¹⁾, A. Georgakilas²⁾, K. Zekentes²⁾, G. Halkias²⁾, ¹⁾ INSA de Lyon, Villeurbanne, France, ²⁾ Foundation for Research and Technology-Hellas, Crete, Greece.

39- Burst Noise in Reverse and Forward Current in the Lattice-Mismatched InP/In_{1-x}Ga_xAs/InP Photodetector Array. D. Pogany, S. Ababou, F. Ducroquet, G. Guillot, INSA de Lyon, Villeurbanne, France.

41- Atomic Scale Simulation of Lattice Mismatched Heterostructures : Case of CdTe/GaAs. M. Djafari Rouhani¹⁾, A. Sahlaoui²⁾, A.M. Gué²⁾, D. Estève²⁾, ¹⁾ Université P. Sabatier, Toulouse, France, ²⁾ LAAS-CNRS, Toulouse, France.

43- Transport Processes in Au/n-InP and Au/Oxyde/n-InP Devices Treated in Oxygen Multipolar Plasma. P. Renard¹⁾, S. Ravelet¹⁾, C. Simon²⁾, A. Bouziane²⁾, B. Lepley³⁾, ¹⁾ ESSTIN, Vandoeuvre-lès-Nancy, France, ²⁾ Université de Nancy, Vandoeuvre-lès-Nancy, France, ³⁾ Université de Metz, Metz, France.

44- Determination of Refractive Indexes of InGaAlAs/InP in the Wavelength Range from 300 to 1900 nm by Spectroscopic Ellipsometry. H.W. Dinges, H. Burkhard, R. Lösch, H. Nickel, W. Schlapp, Deutsche Bundespost Telekom Forschungsinstitut, Darmstadt, Germany.

46- Hall Mobility Profiling in HEMT Structures. F. Djamdji¹⁾, R. Blunt²⁾, ¹⁾ Bio-Rad Microscience Ltd, Hemel Hempstead, UK, ²⁾ Epitaxial Products International Ltd, Cardiff, UK.

49- The Lattice Parameter Variation of InP Homoepitaxial Layers Grown by HVPE. D. Arivuoli¹⁾, G. Attolini²⁾, C. Bocchi²⁾, C. Pelosi²⁾, ¹⁾ Anna University, Madras, India, ²⁾ MASPEC, Parma, Italy.

51- Evidence For Nonuniform Interface Thickness in Strained GaInAs/InP Quantum Wells. J. Camassel¹⁾, K. Wolter²⁾, S. Juillaguet¹⁾, R. Schwedler²⁾, E. Massone¹⁾, B. Gallmann²⁾, J.P. Laurenti³⁾, ¹⁾ Université de Montpellier II, Montpellier, France, ²⁾ RWTH Aachen, Germany, ³⁾ Université de Metz, Metz, France.

52- A Controllable Mechanism of Forming Extremely Low Resistance Non-Alloyed Contacts to Group III-V Compound Semiconductors. G. Stareev, Heinrich-Hertz-Institut, Berlin, Germany.

112-Modification of Semiconductor-Native Oxide Interfaces During Oxidation of Some III-V Semiconductors. I.A. Aizenberg and I.I. Aparshina, Russian Academy of Sciences, Moscow, Russia.

53- Investigations of the n-GaAs/Electrolyte Interface with Time-Resolved Photoluminescence. O. Krüger, Ch. Jung, Humboldt-Universität, Berlin, Germany.

54- Evaluation of ZnSe and ZnTe MOVPE Epitaxial Layers from Photoluminescence and Cathodoluminescence Studies. B.E. Ponga¹⁾, T. Cloitre¹⁾, E. Molva²⁾, O. Briot¹⁾, J. Calas¹⁾, R.L. Aulombard¹⁾, ¹⁾ Université de Montpellier II, Montpellier, France, ²⁾ LETI-CENG, Grenoble, France.

56- Characterization of Ohmic Contacts on N and P Type GaSb. E. Villemain, S. Gaillard, M. Rolland, A. Joullié, Université de Montpellier II, Montpellier, France.

57- Characterization of Tandem and Polysrystalline GaAs Devices by Ligth Beam Induced Current Mapping. H. Soumana, J.P. Boyeaux, M. Gavand, L. Mayet, A. Laugier, INSA de Lyon, Villeurbanne, France.

— **60- The Effects of Sampling Grid Density on Process-Control Values Derived from Spatially Resolved Photoluminescence Measurements.** C.J.L. Moore, J. Hennessy, Waterloo Scientific Inc, Waterloo, Ontario, Canada.

61- Non-Destructive, Whole Wafer Assessment of Optoelectronic Materials by Scanning Photoluminescence. M. Bugajski¹⁾, P. Edelman²⁾, J. Ornoch¹⁾, M. Wesolowski¹⁾, W. Lewandowski¹⁾, ¹⁾ Institute of Electron Technology, Warsaw, Poland, ²⁾ University of South Florida, Tampa, FL, USA.

62- Dependence of Surface Morphology and Dislocation Structure in Lattice Mismatched InGaAs/ InP Heterostructures Investigated by AFM and TEM. L. Porte¹⁾, M. Gendry¹⁾, G. Hollinger¹⁾, J.L. Loubet¹⁾, C. Miozzi²⁾, M. Pitaval²⁾, ¹⁾ Ecole Centrale de Lyon, Ecully, France, ²⁾ Université Lyon I, Villeurbanne, France.

66- Stress Relaxation in the Buffer Layers of (Cd,Zn)Te Heterostructures. J. Calatayud, J. Allègre, H. Mathieu, Université de Montpellier II, Montpellier, France.

67- Investigation of GaSb Substrates by Scanning Photoluminescence. H. L'Haridon¹⁾, R. Callec¹⁾, P.N. Favennec¹⁾, Y. Le Guillou¹⁾, A. Gouskov²⁾, C. Kingelhöfer³⁾, S.K. Krawczyk³⁾, M. Garrigues³⁾, ¹⁾ CNET, Lannion, France, ²⁾ Université de Montpellier II, Montpellier, France, ³⁾ Ecole Centrale de Lyon, Ecully, France.

69-Electronic Structure of (Ga,In)As- (Ga,Al)As Strained-Layer Quantum Wells Grown on Relaxed Buffer Layers. D.J. Dunstan¹⁾, B. Gil²⁾, ¹⁾ University of Surrey, Guilford, UK, ²⁾ Université de Montpellier II, Montpellier, France.

71- Characterization of the Crystallographic Defect Structure in Selected Area Epitaxial Growth of GaInAs on InP by Metalorganic Chemical Vapour Deposition. R.E. Mallard¹⁾, E.J. Thrush²⁾, M.A. Gibbon²⁾, G.R. Booker¹⁾, ¹⁾ Oxford University, Oxford, UK, ²⁾ Bell-Northern Research Europe Ltd, Essex, UK.

73- Raman Investigation of Photocarrier Properties in Both Undoped and Fe-Doped InP Substrates. B. Boudart, B. Mari, B. Prevot, IN2P3-CNRS, Strasbourg, France.

74- Photo-EPR of the Anion Antisite in InP. A. Goltzene, B. Meyer, C. Schwab, IN2P3-CNRS, Strasbourg, France.

75- Effective N-Type Doping of InP by the Neutron Transmutation Technique. B. Mari¹⁾, B. Prevot²⁾, C. Schwab²⁾, ¹⁾ Universitat Politècnica de València, València, Spain, ²⁾ IN2P3-CNRS, Strasbourg, France.

78- Characterization of the Homogeneity of Semi-Insulating InP and GaAs by Spatially Resolved Photocurrent. P. Martin, M.A. Gonzalez, L.F. Sanz, M. Chafai, J. Jiménez, ETTSII & Facultad de Ciencias, Valladolid, Spain.

79- Raman Characterization of GaAs Doped with Tin by Laser Assisted Diffusion. J. Jiménez¹⁾, E. Martín¹⁾, B.J. García²⁾, J. Piqueras²⁾, ¹⁾ ETTSII & Facultad de Ciencias, Valladolid, Spain, ²⁾ Universidad Autonoma de Madrid, Madrid, Spain.

83- In-Line Control of the Fabrication of Lattice Mismatched Photodiodes by Integrated and Spectrally Resolved Scanning Photoluminescence. C. Kingelhöfer¹⁾, K. Schohe²⁾, S.K. Krawczyk¹⁾, B. Vilotitch³⁾, X. Hugon³⁾, ¹⁾ Ecole Centrale de Lyon, Ecully, France, ²⁾ Scantek, Ecully, France, ³⁾ Thomsom TMS, St-Egrève, France.

84- Improvement in the DLTS Analysis of Defect Levels. E. Losson¹⁾, B. Lepley¹⁾, K. Dmowski²⁾, ¹⁾ Université de Metz, Metz, France, ²⁾ University of Technology, Warsaw, Poland.

85- Non-Destructive Mapping Semiconducting Layers Using a Microwave Device. C. Druon, N. Belbounagua, P. Tabourier, J.M. Wacrenier, Université des Sciences et Techniques de Lille, Villeneuve d'Asq, France.

86- Evaluation of MBE Grown GaAlAs/GaAs and AlAs/GaAs Multilayered Structures. C. Frigeri¹⁾, R. Hey²⁾, B. Jenichen²⁾, ¹⁾ MASPEC, Parma, Italy, ²⁾ ZIE Institute, Berlin, Germany.

89- The Bulk and Surface States of GaSb/ AlSb/ InAs Supperlattice. M.D. Rahmani, P. Masri, Université Montpellier II, Montpellier, France.

92- Contribution to Analysis of PL Intensity. D.A. Etcheberry, CNRS-LEI, Meudon, France.

93- EBIC Characterization of LEC GaAs. C. Frigeri, MASPEC, Parma, Italy.

104- SEM Characterization of Compound Semiconductors. E.B. Yakimov, Russian Academy of Sciences, Moscow, Russia.

105- Non-Destructive Characterization of Bulk Distribution of Electro-Physical Properties in Semiconductor Structures. O. Kononchuk, N.G. Ushakov, E.B. Yakimov, S.I. Zaitsev, Russian Academy of Sciences, Moscow, Russia.

WEDNESDAY, MAY 20, 1992

(8:30 - 10:15)

Session n° 1 : Performance and reliability of micro-optoelectronic devices in connection with material properties and process conditions - I

Chairman : D. Lile, Colorado State University, Fort Collins, USA

8:45 -9:15 INVITED LECTURE

"Material Related Issues and Their Characterization in View of III-V Heterojunction Device Optimization"

D. Pavlidis, The University of Michigan, Ann Arbor, USA

9:15 -9:30

Material Problems for the Development of InGaAs/InAlAs HEMTs Technology. K. Zekentes¹, G. Halkias¹, A. Dimoulas¹, N. Kornilos¹, A. Tabata², T. Benyattou², G. Guillot², J.R. Morante³, F. Peiro³, A. Cornet³, A. Georgaklias⁴, A. Christou⁴, ¹ Foundation for Research and Technology-Hellas, Crete, Greece, ² INSA de Lyon, Villeurbanne, France, ³ Universitat de Barcelona, Barcelona, Spain, ⁴ University of Maryland, College Park, MD, USA.

9:30 -9:45

Theoretical and Experimental Study of Failure Mechanisms in RF Reliability Life Tested HEMTs. W.T. Anderson¹, K.A. Christianson¹, C. Moglestue², ¹ Naval Research Laboratory, Washington, DC, USA, ² Fraunhofer-IAF, Freiburg, Germany.

9:45 -10:00

A Study of Detrimental Transient Effects in GaAs HEMTs. J.M. Dumas¹, P. Audren², M.P. Favennec², S. Mottet¹, D. Lecrosnier¹, M. Gauneau¹, ¹ CNET, Lannion, France, ² Institut Universitaire de Technologie, Lannion, France.

10:00 - 10:15

Relating μ -Wave Mapped Data to Physical Parameters for MODFETs. J. Braunstein, P.-J. Tasker, M. Schlechtweg, A. Hülsmann, G. Kaufel, K. Köhler, Fraunhofer-IAF, Freiburg, Germany.

Material Related Issues and Their Characterization in View of III-V Heterojunction Device Optimization

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Device Optimization depends strongly not only on design, process and characterization, but also on the profound understanding of material related issues. Trap related effects in many III-V devices can, for example, result in changes of electrical characteristics at low frequencies or upon cooling. The transconductance (g_m) and output resistance (R_{ds}) of FET's can differ significantly at low and high frequencies. A study of InAlAs/InGaAs HEMTs with lattice-matched and strained composition revealed that the channel under the gate, rather than the access region, is responsible for the R_{ds} dispersion. AC conductance characterization showed that interface state densities in such heterostructures correlate well with g_m , R_{ds} dispersion and are maximum ($2.70 \times 10^{12} \text{cm}^{-2} \text{eV}^{-1}$) for 53% In and minimum ($1.98 \times 10^{12} \text{cm}^{-2} \text{eV}^{-1}$) for 60% in the channel.

Similar studies were carried out for other material systems and included low frequency noise characterizations as a function of temperature. They revealed at low temperature a deep trap at 0.27eV in AlGaAs/GaAs HEMT's which induced current collapse. No deep trap was found in GaInP/GaAs HEMT's, but a trap at 0.58eV was found in this system, which may affect the high temperature performance of the device.

Structural changes may also occur during various processing steps, device operation or thermal stressing. Examples of them are generation of defects in various parts of the device, diffusion of dopants across the heterojunction and strain relaxation. Thermal stress of InAlAs/InGaAs HEMT's was found to result in current reduction. A study of the threshold voltage (V_T) shift when a negative gate bias is applied to the device while it is cooled down shows that this only occurs in thermally stressed samples. The results suggest carrier trapping below the channel for thermally stressed HEMT's. The identification of a trap filled voltage limit (V_{tfl}) in these devices provides additional evidence of this effect.

The information obtained from various material characterization techniques, such as X-Ray Diffractometry, SIMS, PL, XEDS, and its usefulness for III-V device optimization, and in particular HEMT's, will be discussed. Electrical characterization of devices complements the evaluation and will also be reported.

Work supported by ARO (Contract No. DAAL03-87-K-0007) and NASA (Contract No. NAGW-1334).

MATERIAL PROBLEMS FOR THE DEVELOPMENT OF InGaAs/InAlAs HEMTs TECHNOLOGY

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ABSTRACT

The InP based In_xGa_{1-x}As/In_{0.52}Al_{0.48}As HEMT devices are being the highest speed devices available today from semiconductors and would result in a significant performance impact at high frequencies when they are incorporated in Microwave Monolithic Integrated Circuits (MMICs). However, such a level of application necessitates that material and device processing issues have been resolved at the discrete device level. Our studies have shown that material problems [1,2] might arise in the InGaAs/InAlAs on InP system which may affect the performance, reproducibility and stability of devices.

Molecular Beam Epitaxy (MBE) was used to grow In_xGa_{1-x}As/In_{0.52}Al_{0.48}As structures of HEMTs, single (SQW) and multiple (MQW) quantum wells, with In_{0.52}Al_{0.48}As buffer layers on InP(001) substrates. The layers were characterized by a variety of techniques including TEM, PL, PR and C-V measurements, and HEMT devices were fabricated and tested. Our results indicated that material quality problems of the In_{0.52}Al_{0.48}As buffer layers strongly affect the heterostructures properties. The PL and PR linewidths obtained from SQWs, MQWs and HEMT channels, increase proportionally to the InAlAs buffer linewidths which is due to the combined effect of interface roughness, alloy clustering and crystal defects. The lowest measured 6°K PL linewidth of InAlAs was 10.9meV and is attributed to short range clustering in this material. Larger optical spectroscopy linewidths, were obtained for layers which exhibited the presence of extended crystal defects (threading dislocations and stacking faults). The extended defects were produced either from imperfections on the InP substrate surface or because of InAlAs growth under low growth kinetics (substrate temperature less than 530°C). A high electron trap density located mainly in the InP/InAlAs interface region was also observed for the lower growth temperatures which gives rise to the kink effect in HEMTs [1]. The higher growth temperatures reduced dramatically the crystal defect density while also improving the heterostructure interface abruptness. An optimum growth temperature of 530°C was determined from the defect studies. Growths at higher temperatures do not result in additional improvement while at the higher examined temperature of 590°C a coarse structure related with strain inhomogeneities was observed [2].

In conclusion, the InGaAs/InAlAs on InP HEMT material quality is dramatically sensitive to small variations in MBE growth conditions, such as InP pregrowth thermal cleaning and growth temperature. In addition, small unintentional strain always exists in this material system grown on InP substrates, which may seriously affect the device stability.

[1] A. Georgakilas, K. Zekentes, N. Kornilios, G. Halkias, A. Dimoulas, A. Christou, F. Peiro, A. Cornet, T. Bonyattou, A. Tabata, G. Guillot, "Suppression of the kink effect in InGaAs/InAlAs HEMTs grown by MBE by optimizing the InAlAs buffer layer", in "4th Int. Conf. on InP and Relat. Mat.", April 21-24, 1992, Newport, RI, USA.

[2] F. Peiro, A. Cornet, J.R. Morante, A. Georgakilas, G. Halkias, "Dependence of the defects present in InAlAs/InP on the substrate temperature", in "1991 MRS Fall Meeting, Symposium E", Dec. 2-6, 1991, Boston, MA, USA. (Paper E5.36).

Theoretical and Experimental Study of
Failure Mechanisms in RF Reliability
Life Tested HEMTs

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A theoretical and experimental study was carried out to investigate the failure mechanisms in high electron mobility transistors (HEMTs). Monte Carlo particle model simulations were made to study the deterioration of transconductance, threshold bias and drain current as a result of RF reliability life testing at ambient temperatures of 175°, 200°, and 225°. Failure as a result of the life testing [1] was defined as a 20 % decrease in the drain current. In the failed HEMT it was also found that the peak transconductance was reduced and shifted to lower gate bias. The transistors, which were fabricated and life tested as reported previously [2], consist of a 40 nm thick Al_{0.26}Ga_{0.74}As layer doped n-type at $2 \times 10^{18} \text{ cm}^{-3}$ interspersed between a 50 nm n-type cover of GaAs doped at $7 \times 10^{18} \text{ cm}^{-3}$ and an undoped 0.8 μm thick undoped GaAs layer on an AlGaAs-GaAs superlattice. The gate metal was a standard layered structure of Ti, Pt, and Au, and standard Au-Ge-Ni alloy was used for the Ohmic contacts. The possible failure mechanisms considered are:

- i) Migration of metal from the Schottky contact into the AlGaAs layer reducing its effective thickness (sinking gate) and a resulting change in the Schottky barrier height.
- ii) Ohmic contact degradation possibly by interdiffusion of metal into the GaAs and a consequent trapping of electrons establishing a barrier against the current flow through it.
- iii) Diffusion of aluminium from the AlGaAs layer into the GaAs, whereby the conduction band discontinuity at the heterojunction reduces (deconfinement of the 2 DEG).
- iv) Diffusion of the dopant silicon, impurities or defects from the AlGaAs into the GaAs, reducing the carrier mobility and the saturation velocity of the carriers in the 2 DEG channel.
- v) Redistribution of dopant silicon in the AlGaAs layer reducing the average doping level and effective thickness of the undoped spacer layer.
- vi) Surface states near the gate result in a reduced 2 DEG current.

To check the validity of these possible failure mechanisms, the electrical properties of the transistor have been simulated by Monte Carlo particle modelling [3]. This technique, which considers transport of individual particles from first physical principles in detail, represents a space and time self-consistent quasicontinuous solution of Boltzmann's transport and Poisson's field equation. Experimental studies included transconductance dispersion as a function of frequency, source resistance, transconductance and threshold voltage shifts, and SEM examinations.

From this study it is concluded that the possible reasons for the failure of the heterojunction transistors following RF life testing is a partial alloying of gate metal into the AlGaAs layer (sinking gate) resulting in a reduced AlGaAs thickness between the gate metal and the 2 DEG and an increase in Ohmic contact resistance, e.g. by an accumulation of trapped carriers in the Ohmic contact regions establishing a barrier reducing the current flow through them. The observed reduction in the gate threshold can be explained by the sinking gate, not by an increase in the Ohmic contact resistance, while the change in shape of the I/V curves can only be explained by an increase in source resistance.

References:

1. Navy Contract No. N00014-86-C-2547, Final Report, March 1988.
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A STUDY OF DETRIMENTAL TRANSIENT EFFECTS IN GaAs HEMTs

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The GaAs FET-based integrated circuits (IC) performances can be limited by anomalous effects such as transients on the drain current or output voltage. As a consequence, the small signal voltage gain in analog circuits and the propagation delay in digital circuits are degraded. These effects have been (and are still) studied in the GaAs MESFET ; now the GaAs HEMT is under investigation and this contribution deals with results obtained from this device.

Drain current transients have been studied in MBE and MOCVD-grown AlGaAs/GaAs conventional and AlGaAs/InGaAs/GaAs pseudomorphic HEMTs. They were issued from foundry services and fabricated with technological standards. The gate lengths were 0.25 and 0.50 μm .

The drain current has been characterized under gate switching conditions (the device being biased in the saturation region) by means of isothermal relaxation experiments. The full transient curves have been then digitalized which gives better accuracy and multiexponential discriminating capabilities than the classical DLTS.

The drain current transients have been found to be governed by free carrier emission and/or capture processes from deep levels :

- Deep levels related to chromium (Cr) have been observed for both MBE-grown conventional and pseudomorphic HEMTs supplied one manufacturer. The following signatures : $E_{na} = 0.68 \text{ eV}$, $\sigma_{na} = 2.1 \times 10^{-15} \text{ cm}^{-2}$ (EF1) and $E_{na} = 0.50 \text{ eV}$, $\sigma_{na} = 2.1 \times 10^{-17} \text{ cm}^{-2}$ (see Bhattacharya et al., JAP, 52 (12), 1981, 7224) for the emission processes and $E_{pa} = 0.91 \text{ eV}$, $\sigma_{pa} = 5 \times 10^{-15} \text{ cm}^{-2}$ (HL1) for the capture process have been clearly identified. The total concentration, N_t , is greater than 10^{15} cm^{-3} . SIMS profiles confirmed that Cr outdiffused from the substrate up to the AlGaAs/GaAs or InGaAs interface vicinity. No drain current transient component was due to trap(s) relevant of strained layers, even in thermodynamically metastable structures.

- Emission-type transients measured in MBE-grown conventional HEMTs supplied by another manufacturer were governed by traps induced by an electron photolithography process. The following signatures have been observed : $E_{na} = 0.7 \text{ eV}$, $\sigma_{na} = 2 \times 10^{-13} \text{ cm}^{-2}$ (EB4) together with $E_{na} = 0.9 \text{ eV}$, $\sigma_{na} = 6 \times 10^{-11} \text{ cm}^{-2}$ (EB3). The total concentration, N_t , was around 10^{15} cm^{-3} . Moreover, these traps localized at the AlGaAs/GaAs interface vicinity were responsible for the degradation of the Noise figure : an increase of 0.5 dB at $F = 12 \text{ GHz}$.

These experiments clearly point out that the drain current transient effects detrimental to the IC operation of the GaAs HEMT are strongly dependent on the technological processing steps and material. However they can be investigated and subsequent improvements carried out.

Relating μ -Wave Mapped Data to Physical Parameters for MODFETs

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Abstract

Modulation doped $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$ high electron mobility transistors (HEMT) were statistically characterized at μ -wave frequencies to investigate transistor reliability and reproducibility to allow the design of multi stage low noise amplifiers (LNAs)¹.

As circuit complexity increases transistor reproducibility from die to die, from wafer to wafer, and from lot to lot becomes more and more important. In the fabrication of short gate length transistors (smaller than $0.5\ \mu\text{m}$), for mm-wave applications, the critical step is gate processing. We report on the statistical μ -wave characterization of MODFETs with e-beam lithography defined gates which were recessed with RIE to selective etch stops.

A computer controlled automatic measurement setup was developed for on wafer characterization. It consists of an automatic wafer prober (Electroglas 2001X), a DC and an S-parameter measurement system. Full DC and RF characterization, and wafer mapping can thus be carried out.

The measured S-parameters when converted to Y-parameters give directly the transistor extrinsic circuit model element values; input capacitance and resistance, feedback capacitance and resistance, and in the output circuit transconductance, transit time, output capacitance and conductance. To obtain information on intrinsic circuit model elements which can be related directly to the intrinsic physical parameters a pre-investigation of the parasitic elements is necessary. Parasitic pad capacitances were measured on isolated test structures. The fringing capacitance on the sides of the gate was extracted from measurements of active transistors with different gate lengths and widths. The parasitic capacitances show only a very small scatter and are not sensitive to the processing conditions. In order to extract intrinsic transconductance the source resistance for each measured device has to be determined.

Example

On a two inch wafer with a 95% yield $100\ \mu\text{m}$ wide MODFETs were measured. The designed gate length was $0.35\ \mu\text{m}$. The extrinsic R_s and g_m were $0.5753\ \Omega\text{mm}$ with a standard deviation of $0.0212\ \Omega\text{mm}$ and $499.487\ \text{mS/mm}$ with a standard deviation of $4.135\ \text{mS/mm}$, respectively. The resulting intrinsic g_m of $654.984\ \text{mS/mm} \pm 9.135\ \text{mS/mm}$ gives a thickness of $335\ \text{\AA} \pm 5\ \text{\AA}$ when the saturated velocity model is applied.

As the intrinsic gate capacitance C_g is a function of thickness and gate length it is important to show that the thickness which is determined by MBE growth and recess etching is constant. Then C_g can be related to gate length. Calculating C_g takes the pad and fringing capacitances and the $g_m R_s$ correction into account. Measured extrinsic values were for C_{gs} $0.981\ \text{pF/mm} \pm 2.12\ \text{fF}$ and for C_{gd} $0.232\ \text{pF/mm} \pm 0.56\ \text{fF}$. Using the extracted values a gate length of $0.335\ \mu\text{m} \pm 90\ \text{\AA}$ was calculated. This is in good agreement with SEM investigations which can only be carried out after cleaving the wafer.

¹ "Design and Characterization of High Performance 60 GHz Pseudomorphic MODFET LNAs in CPW Technology Based on Accurate S-Parameter and Noise Models", M. Schlechtweg et al., to be published at the IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium 1992, Albuquerque, NM

WEDNESDAY, MAY 20, 1992
(10.30 - 12:00)

Session n° 2 : Performance and reliability of micro-optoelectronic devices in connection with material properties and process conditions - II

Chairman : H.L. Hartnagel, THD, Darmstadt, Germany

10:30-11:00 INVITED LECTURE

"Material Related Reliability Aspects of III-V Optical Devices"
O. Ueda, Fujitsu Laboratories Ltd., Atsugi, Japan

11:00 - 11:15

A Possible Origin of Degradation Mechanisms in AlGaAs/GaAs Laser-Like Structures.
B. Sieber¹⁾, J.L. Farvacque¹⁾, J. Wang²⁾, J.W. Steeds²⁾, ¹⁾ Université des Sciences et Technologies de Lille, Villeneuve d'Ascq, France, ²⁾ University of Bristol, Bristol, U.K.

11:15 - 11:30

Thermal Stability of Pseudomorphic HEMTs. **A.A. Rezazadeh¹⁾, N.L. Saunders²⁾, D.V. Morgan²⁾, H. Thomas²⁾, R.S. Smith³⁾, P. Kirby³⁾, ¹⁾ King's College, London, U.K., ²⁾ University of Wales, Cardiff, UK, ³⁾ GEC Hirst Research Center, Wembley, UK.**

11:30 - 11:45

Detailed Process Analysis for Controlling the Yield of GaAs MMIC's Technology
J.L. Pinsard, A. Kalfane, Thomson Composants Microondes, Orsay, France.

11:45 - 12:00

Spatially Resolved Photoluminescence Techniques Applied to the Control of InGaAsP/ InP Laser Processing. **A. Guichardon¹⁾, M. Boulou¹⁾, A. Duick²⁾, J.L. Gentner²⁾, ¹⁾ Alcatel Alsthom Recherche, Marcoussis, France, ²⁾ Alcatel CIT/OCD, Marcoussis, France**

Materials related reliability aspects of III-V optical devices

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This paper describes the current understanding of materials issues in III-V compound semiconductor heterostructures and degradation of optical devices, lasers and LEDs fabricated from these materials.

Defect generation and structural imperfections due to thermal instability of crystal are among these issues. Defects introduced during growth are classified into two types; interface defects, i.e., misfit dislocations, inclusions, stacking faults, and microtwins, and bulk defects, i.e., structural or non-structural precipitates and faulted or unfaulted loops. Structural imperfections due to thermal instability of the crystal are also found. They are modulated structures due to spinodal decomposition of the crystal and ordered structures due to rearrangement of deposited atoms on the growth surface. In each phenomenon, the nature and generation mechanism of defect/structures are clarified.

For the degradation of III-V optical devices, we will discuss three major degradation modes; rapid degradation, gradual degradation, and catastrophic failure. Rapid degradation occurs via either recombination-enhanced dislocation climb (REDC) or glide (REDG). For ease with which these phenomena occur in different heterostructures is examined. Based on the results, the dominant parameters for the REDC and REDG processes are discussed. Gradual degradation presumably results from a recombination-enhanced point defect reaction in GaAlAs/GaAs-based optical devices. This mode is also enhanced by thermal stress due to lattice-mismatch. However, we do not observe such degradation in InGaAsP/InP-based optical devices. Catastrophic failure is found to be due to catastrophic optical damage (COD) at a mirror or at a defect. In each degradation mode, the influence of the defects/structures on the degradation is discussed and methods for elimination of degradation are proposed.

A POSSIBLE ORIGIN OF DEGRADATION MECHANISMS IN AlGaAs/GaAs LASER-LIKE STRUCTURES

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AlGaAs/GaAs lasers are subjected, when operating, to degradation mechanisms which appear, with time, in the form of Dark Line Defects (DLDs). The development of DLDs is not systematic, and the details depend on the nature of particular areas of the sample.

Artificial degradation experiments were performed with the use of a 10 kW/cm² krypton laser to identify 'sensitive' and 'insensitive' areas of a Al_{0.4}Ga_{0.6}As/GaAs/Al_{0.17}Ga_{0.83}As sample. The complete degradation of 'sensitive' regions was achieved after a delay of the order of 15 hours. In other ('insensitive') regions, no degradation was observed within the time of the experiments.

Aluminium fluctuations of AlGaAs layer deposited on GaAs were deduced, in 'sensitive' regions, from local scanning transmission electron microscope (STEM) cathodoluminescence spectra recorded at 30K. No fluctuation could be detected in 'insensitive' areas of the sample.

Even if the lattice mismatch is very low for such epitaxial layers, such composition fluctuations can be seen as one possible origin of degradation mechanisms of optical devices. They induce stress variations, of the order of 1 MPa, which are large enough to induce photoplastic glide of dislocations. The optical contribution to dislocation glide is roughly estimated to 0.9 eV. It is much more likely to correspond to electronic transitions at a dislocation reconstruction defect than to transitions related to dislocation intrinsic bands.

Thermal Stability of pseudomorphic HEMTs

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ABSTRACT

The development of reliable integrated circuits is based on the assurance of device longevity under nominal environmental and electrical conditions and survivability of devices in the presence of overstress. The reliability and stability of advanced microwave devices and pseudomorphic structures subjected to heat treatment is of particular importance for device applications since most device processing schemes include high temperature anneals. Several studies have indentified reliability and failure mechanisms of GaAs technology but there is little or no information about the reliability of pseudomorphic HEMTs (PHEMTs) in the open literature.

This study reports the reliability of PHEMTs and establishes the working life and failure mechanisms. Attention has focused on the ohmic contacts, Schottky contact and quantum well channel. Accelerated life tests on devices and ohmic contact test patterns have been coupled with thermal stability tests on heterojunction material.

DETAILED PROCESS ANALYSIS FOR CONTROLLING THE YIELDS OF GALLIUM ARSENIDE MMIC's TECHNOLOGY

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Abstract : In order to evaluate the technical parameters which control the yields of the Gallium Arsenide MMIC's technology, we measure the effect of the following parameters : the gallium arsenide bulk resistivity, the doses used for the channel implant, the thickness of the silicon nitride encapsulation layer, the recess etched current.

The choice is based on a pre-evaluation done with GATES (GATEWAY MODELING, INC.), a technological software.

The main result is the quantification of the effect on the electrical parameters (such as the pinchoff voltage, the saturation current, the transconductance, etc...) when the technology is submitted to a known variation of some key process parameters.

The variation is about three times larger than the expected fluctuation for each parameter, such a deviation is usefull to extract the effect from the noise.

In this way, we classify the technical parameters by their effects on the yield. We show that the most significant parameters are the thickness of the silicon nitride layer and the recess etched current. A total variation of twenty angstroms of the thickness of the silicon nitride on 500 angstroms induces a variation of 2 mA on 15 mA on the saturation current.

The recess etched current is used to adjust the thickness of the channel but it acts as a feedback parameter which influence the effect of the other parameters. We discuss this behavior in order to have a proper interpretation of the effects.

On the other hand, a lot of electrical variables are measured during the process. The question arises which variables amongst these provide the maximum information.

To face this question, we classify the main electrical variables on the basis of their correlations by a Principal Component Analysis. This analysis shows the role of the schottky junction in the variance of the other variables.

This work is supported by the French Ministry of Defence (DRET).

SPATIALLY RESOLVED PHOTOLUMINESCENCE TECHNIQUES APPLIED TO THE CONTROL OF InGaAsP/InP LASER PROCESSING.

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Characterization by photoluminescence of optoelectronic structures is particularly important for process optimization. A high resolution technique in the micro-range is necessary for the evaluation of laser structures. In this report we present observations of buried laser stripes by infrared luminescence microscopy and scanning photoluminescence.

The infrared microscope is equipped with a PbS detector (ideal for imaging the 1.3 - 1.5 μm wavelength range with a vidicon camera). Two different lasers were used as light sources for photocarrier generation. A YAG laser (1.06 μm) with absorption in the active layer, gives direct excitation of carriers. An Argon laser (0.514 μm) with absorption in the upper InP confinement layer, yields by diffusion indirect excitation. A single objective is used for the source and for the luminescence collection. In order to image a large area on the sample, the laser beam is unfocused on the observation plane. Power excitation can vary up to 500 W/cm². A semi-quantitative analysis can be performed using the intensity of the video signal.

A scanning photoluminescence apparatus (IMAGEUR SCAT) fitted with an HeNe and a YAG source, has also been used for this evaluation. In this case the laser beam is focussed and scanned across the sample surface giving a theoretical spatial resolution of about one micrometer.

Both characterization techniques have been used to evaluate laser structures consisting of MQW active layers emitting at 1.5 μm grown by GSMBE (Gas Source MBE). Two different laser structures of 2 μm stripe width have been investigated ; the samples include both the stripe and an unetched control region. The first structure is a high quality Double Channel Planar Buried Heterostructure (DCPBH) fabricated with an LPE regrowth, and serves as the reference. The second consists of a 2 μm width stripe buried by an InP layer grown by GSMBE.

We have observed a difference in luminescence intensity of the stripe as compared to the unetched broad area region on the same sample. The analysis of the variation of the luminescence makes it possible to characterize the quality of the regrown interface. This information can be further analysed by looking to the laser characteristics (threshold current, quantum efficiency) in order to understand physical effects such as homojunction leakage current and heterointerface recombination.

Further results will be presented for the two photoluminescence techniques, on samples prepared using dry and wet etching and different regrowth processes, as well as the influence of surface preparation on luminescence properties.

WEDNESDAY, MAY 20, 1992

(14 :00- 16:45)

Session n° 3 : Growth and characterization of epitaxial structures

**Chairman : G. Salmer, Université des Sciences et Technologies de Lille,
Villeneuve d'Ascq, France.**

14:00 - 14:30 INVITED LECTURE

"Atomic Ordering and Phase Separation in Compound Semiconductors and their Effect on Device Behavior"

S. Mahajan, Carnegie Mellon University, Pittsburgh, USA

14:30 - 15:00 INVITED LECTURE

"Improved Device Quality by Strained Layer Epitaxy"

H. Beneking, RWTH Aachen, Germany

15:00 - 15:15

**II-VI Semiconductor Strained Heterostructures : A Structural Review. G. Feuillet, CENG,
Grenoble, France.**

15:15 - 15:30

Interface Properties of Strained InGaAs/InP Quantum Wells Grown by LP-MOVPE.

R. Schwedler¹⁾, B. Gallmann¹⁾, K. Wolter¹⁾, A. Kohl¹⁾, K. Leo¹⁾, H. Kurz¹⁾, F.H. Baumann²⁾,

¹⁾ RWTH Aachen, Germany, ²⁾ AT&T Bell Laboratories, Holmdel, NJ, USA

15:30 - 15:45

**Raman Scattering in In_xGa_{1-x}As/GaAs Superlattices Grown by MBE. M. Constant, N. Matrullo,
A. Lorriaux, R. Fauquembergue, Y. Druelle, J. Di Persio, Université des Sciences et Techniques
de Lille , Villeneuve d'Ascq, France.**

15:45 - 16:00

Non-Destructive Approaches of Interdiffusion Phenomena Across InGaAs/InGaP Interfaces :

Photoluminescence versus Raman. H. Peyre¹⁾, S. Juillaguet¹⁾, E. Massone ¹⁾, J. Camassel¹⁾,

F. Alsina²⁾, J. Pascual²⁾, R.W. Glew³⁾, ¹⁾ Université de Montpellier II, Montpellier, France,

²⁾ Dept. Fisica, Bellaterra, Spain, ³⁾ BNR-EUROPE Ltd., Harlow, UK

16:00- 16:15

**Determination of Carrier Densities in AlGaAs/GaAs Heterojunction and Superlattice Structures
by Photoluminescence Spectroscopy. Z.H. Lu, E. Mao, B.W. Kim, A. Majerfeld, University of
Colorado, Boulder, CO, USA.**

16:15 - 16:30

Selective Growth of GaAs and GaAlAs by Cl-Assisted OMVPE at Atmospheric Pressure.

**R. Azoulay, L. Dugrand, A. Izrael, E.V.K. Rao, R. Mellet, A.M. Pougnet, CNET, Bagneux,
France.**

16:30 - 16:45

**Photoluminescence Microscopy Investigation of Lattice Defects in Heterostructures Grown by
MOVPE and MBE. Z.M. Wang, M. Baeumler, K. Bachem, E.C. Larkins, J.D. Ralston,
W. Jantz, Fraunhofer-IAF, Freiburg, Germany.**

ATOMIC ORDERING AND PHASE SEPARATION IN COMPOUND SEMICONDUCTORS
AND THEIR EFFECT ON DEVICE BEHAVIOR

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ABSTRACT

It will be shown that atoms within ternary and quaternary epitaxial layers of III-V compound semiconductors are not distributed at random on their respective sub-lattices. Two types of deviations from randomness are observed: (i) atomic ordering, and (ii) phase separation. Crystallography of these micro-structural features will be highlighted, and their influence on electronic mobility and degradation resistance of light emitting devices will be discussed.

Improved Device Quality by strained layer epitaxy

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A survey is given on the application of strained epitaxial layers onto InP and GaAs.
The layer compositions are GaAs(In) and InP(As) / InP(Ga), respectively.

The principle behaviour of thin strained layers onto GaAs and InP substrates are
shown and the material quality improvement is demonstrated.

Examples are Schottky diodes, bipolar devices and double heterostructure
MODFETs.

References:

- H.Beneking, III-V Technology: The Key for Advanced Devices,
J.Electrochem.Soc. 136, 2680-2686 (1989)
H.Beneking, Strained Layer Epitaxy for Material Quality Improvement,
Proc.First III-V EPI-Conf. Budapest/Hungary 9.-11.4.1990
A.Mesquida Küsters et al., Study of strain effects in high performance double
heterostructure $\text{In}_x\text{Ga}_{1-x}\text{As}$ ($0.57 < x < 0.73$) p-MODFET,
presented at Fourth Internat.Conf. on Indium Phosphide and Related Materials,
April 20-24, 1992

II-VI Semiconductor Strained Heterostructures : A structural review

G. Feuillet
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This talk will be devoted to the structural properties of M.B.E. grown heterostructures of II-VI semiconductors. The emphasis will be put on the critical thicknesses for strain relaxation in epilayers for a variety of systems, on the relaxation mechanism itself, and finally on the interface roughness between layers.

Two growth orientations will be considered, namely (001) and (111), for systems of the type CdTe/Cd_{1-x}Zn_xTe, CdTe/Cd_{1-x}Hg_xTe or CdTe/Cd_{1-x}Mn_xTe.

In the case of (001) oriented layers, strain relaxation occurs via formation and displacement of mainly 60° dislocations which, depending on their type (**a** or **b**) and on the sign of the coherency strain, glide in from the surface towards the interface in a dissociated or contracted form. These dislocations may also interact and form edge type dislocations. For (111) oriented layers, we shall demonstrate that strain relaxation occurs via twinning which may be avoided if one resorts to slightly misoriented growth axes: in this latter case again widely dissociated dislocations are observed to lie on the (111) growth plane.

The critical thicknesses for strain relaxation were determined by a combination of in situ RHEED oscillations, of TEM and of photoluminescence for the mentioned systems, x ranging from 0 to 1; the results are discussed in light of existing models for strain relaxation in lattice mismatched growth.

High resolution TEM was employed to investigate the atomic structure of II-VI semiconductor interfaces by using chemically sensitive diffractions: if one follows the variation of the atomic pattern across the interface one has access to its roughness on the atomic scale. This can be complemented by double crystal X-ray diffraction obtained on superlattices of the same materials from which the interdiffusivity between the constituting layers can be extracted.

Interface properties of strained InGaAs/InP quantum wells grown by LP-MOVPE

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The effects of strain on the interface properties of $\text{In}_{1-x}\text{Ga}_x\text{As}/\text{InP}$ multiple-quantum well structures grown by low pressure metal-organic vapor phase epitaxy (LP-MOVPE) have been investigated using optical spectroscopy and transmission electron microscopy (TEM). We have studied a large number of samples with a composition varying between $0.17 \leq x_{\text{Ga}} \leq 1.00$. The optical studies (photoluminescence, photoluminescence excitation, photoconductivity) exhibit distinct spectral peaks over the whole composition range. We have compared the optical transition energies with detailed calculations of the electronic transitions in strained $\text{In}_{1-x}\text{Ga}_x\text{As}/\text{InP}$ QWs. In all samples, we find evidence for an additional interface layer equivalent to $\text{InAs}_{0.65 \pm 0.05}\text{P}_{0.35 \mp 0.05}$, as already reported for the lattice matched case by Camassel et. al. [1]. This interface layer leads to an apparent increase of the well thickness with respect to the value extrapolated from the growth parameters. For $x_{\text{Ga}} < 0.5$, the peak splitting corresponds to a well thickness difference of 1 monolayer (ML) $\text{In}_{1-x}\text{Ga}_x\text{As}$, whereas spatial variations of the $\text{InAs}_{0.65}\text{P}_{0.35}$ do lead to line broadening only. For $x_{\text{Ga}} > 0.5$, the splitting has a different origin: in this range of compositions, the effect of $\text{In}_{1-x}\text{Ga}_x\text{As}$ layer fluctuations are negligible compared to those originating from the interface layer. The peak splittings observed in optical spectroscopies are well explained by thickness fluctuations of this layer of $\text{InAs}_{0.65}\text{P}_{0.35}$.

The TEM pictures were taken in chemical lattice imaging mode. Most striking feature is a large asymmetry of the interface structure: the lower interfaces (InP to $\text{In}_{1-x}\text{Ga}_x\text{As}$) are rather sharp and show little lateral roughness, whereas the upper interfaces have a transition region of several MLs and considerable lateral roughness on a scale of tens of Å.

In our presentation, we will make a detailed comparison of the optical and TEM results. In particular, we compare the roughness-spectrum deduced from the TEM with the theoretical model used to describe the optical spectra. Both approaches are discussed taking into account their lateral resolutions and their different sensitivities to the composition of the QWs interfaces.

REFERENCES

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RAMAN SCATTERING IN $\text{In}_x\text{Ga}_{1-x}\text{As}$ / GaAs SUPERLATTICES
GROWN BY MOLECULAR BEAM EPITAXY

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The pseudomorphic $\text{In}_x\text{Ga}_{1-x}\text{As}$ /GaAs structures are of particular interest because of the high value of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ electron mobility and the good electron confinement in the ternary alloy.

This paper is concerned with a quantitative determination of strain by Raman scattering in a series of $\text{In}_x\text{Ga}_{1-x}\text{As}$ /GaAs strained-layer superlattices grown by molecular beam epitaxy on (001) surfaces of GaAs substrates. The determination of strain in each type of strained layers was made by investigating frequency shifts between commensurate and incommensurate layers. For this purpose we have measured both Raman phonon frequencies of bulk $\text{In}_x\text{Ga}_{1-x}\text{As}$ alloy samples upon a large scale of composition and Raman phonon frequencies of a series of strained-layer superlattices. The Indium content of bulk $\text{In}_x\text{Ga}_{1-x}\text{As}$ varies from 13 % to 53 %. The compositions of the ternary alloy in the series of superlattices are 4.3 %, 8.5 %, 16 %, 19 % and 22 %. The individual layer thicknesses are constant from sample to sample.

Double crystal X-ray rocking curve (XRC) data on superlattices are compared to those of Raman experiments. This allows a more valid estimation of the obtained results.

NON DESTRUCTIVE APPROACHES OF INTERDIFFUSION PHENOMENA ACROSS InGaAs/InGaAsP INTERFACES: PHOTOLUMINESCENCE versus RAMAN.

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InGaAs quantum wells (QWs), with either InP or InGaAsP barriers, are increasingly considered for optoelectronic device applications. Nevertheless, because interdiffusion across the interfaces (intermixing) results in unwanted modifications of the nominal properties, in-situ controls of the wells composition (to be ultimately done during the processing sequences) are of fundamental interest. Up to now, intermixing at the nanoscale level were mainly investigated by room temperature photoluminescence spectroscopy (PL)^[1] but recent reports^[2,3] have shown Raman to be a powerful (and, maybe, more direct) technique. However, no systematic comparison has been performed on the same series of samples and it is difficult to decide which one is best suited for in-line characterisation.

To compare compositional changes deduced from PL and Raman spectra, we start from a prototype structure made of a single QW of InGaAs (80 Å wide) grown between two thick InGaAsP barriers. They had 0.55 μm (buffer) and 500 Å (cap layer) thicknesses, respectively. Of course all stacking layers were grown lattice-matched to InP. To estimate the amount of intermixing in the case of these InGaAs/InGaAsP interfaces, two different annealing sequences at fixed temperatures of 650 and 750 °C for times up to 2 hours have been performed. Details of the growth conditions and heat treatment can be found elsewhere^[1].

Concerning the experiments, PL has been performed at low temperature (2 K) using the 5145 Å line of an Ar⁺ laser with conventional lock-in detection technics and a cooled Ge detector. The Raman spectra were collected at room temperature, under Brewster angle conditions, through the excitation of the 5017 Å line of another Ar⁺ ion laser. The scattered light was dispersed using a triple monochromator and detected with conventional photon counting technics.

To analyse the blue shift observed in PL, we combine a Green's function approach^[4] with a transfert matrix method and deduce interdiffusion coefficients: $D(650^{\circ}\text{C}) = 9.5 \cdot 10^{-19} \text{ cm}^2.\text{s}^{-1}$ and $D(750^{\circ}\text{C}) = 1.9 \cdot 10^{-17} \text{ cm}^2.\text{s}^{-1}$. From the corresponding concentration profiles, we compute average changes of compositions in the well of about 20 % per hour^{1/2} at 750 °C and only 3 % per hour^{1/2} at 650°C. From Raman, we observe typical frequency shifts for the GaAs-like mode of GaInAs: $\Delta\omega(750^{\circ}\text{C}) = 5.4 \text{ cm}^{-1}$ per hour^{1/2} and $\Delta\omega(650^{\circ}\text{C}) = 0.7 \text{ cm}^{-1}$ per hour^{1/2}. Using appropriate data^[5] for the change in phonon frequency versus composition, we show that both determinations are then in very satisfactory agreement and constitute alternative but equivalent techniques.

1. R.W.Glew et al., Proc. Third Int. Conf. InP and Related Materials. Cardiff 1991.

2. S.J. Yu et al., *J. Appl. Phys.* **70**, 204 (1991).

3. N. Hara and T. Katoda, *J. Appl. Phys.* **69**, 2112 (1990)

4. K.P. Homewood and D.J. Dustan, *J. Appl. Phys.* **69**, 7581 (1991).

5. T. Inoshita, *J. Appl. Phys.* **56**, 2056 (1984).

Determination of Carrier Densities in AlGaAs/GaAs Heterojunction and Superlattice Structures by Photoluminescence Spectroscopy

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We show that low temperature photoluminescence [PL], which is naturally a non-destructive technique, can be used to measure the electron and hole densities in thin and heavily doped GaAs layers in AlGaAs/GaAs heterojunction and Superlattice [SL] structures, particularly in situations when other conventional techniques are not successful or practical. In degenerately doped GaAs the PL emission spectra are dominated by two physical phenomena that shift the spectral energies in opposite directions: band filling and bandgap renormalization [BGR]; this last effect is due to a many-body interaction effect. The measurement method is illustrated by analysis of the 10 K PL spectra of selectively doped SL structures and of NPN Heterojunction Bipolar Transistors [HBT].

For example, for a 50-period SL structure, with wells 52 Å thick and doped with Si to an electron density $n \sim 2 \times 10^{18} \text{ cm}^{-3}$, we observed significant band filling by the electrons confined in the wells. A theoretical analysis assuming optical transitions with $\Delta k = 0$ yields the interband transition energy of the bound states in the wells and a Fermi energy $E_F = 35 \text{ meV}$ above the first bound electron state. The electron density derived from E_F is $1.9 \times 10^{18} \text{ cm}^{-3}$. This density is in very good agreement with Hall measurements and the expected value from doping studies on thicker layers. Similar results were obtained for samples with different well thicknesses. In addition, PL provides structural information on well thickness, heterojunction interface abruptness and roughness, well-thickness reproducibility over the 50 layers, and their uniformity over the wafer surface.

Although band filling is also observed in the low temperature PL spectrum of HBTs, it is not a practical effect for measuring base doping in this type of structure, because of the presence of overlapping emissions from adjacent layers. On the other hand, the BGR effect results in a significant energy shift for $p > 5 \times 10^{18} \text{ cm}^{-3}$ and can usually be resolved in the spectra of these structures. However, quantitative analysis of BGR is hindered due to the distortion of the spectrum by selective reflection from the semi-insulating GaAs substrate. We show that this artifact can generally be removed either experimentally or by theoretical simulation and, therefore, the BGR effect can be properly evaluated. This analysis was used for characterization of the base of HBT structures heavily doped with carbon. Hole densities in the range $10^{19} - 10^{20} \text{ cm}^{-3}$ were measured for structures with bases as thin as $\sim 750 \text{ Å}$. In summary, we show that PL analysis is a powerful tool for the evaluation of heterojunction devices and that it can provide the rapid feedback which is often required for successful iteration in the epitaxial growth process.

SELECTIVE GROWTH OF GAAS AND GAALAS BY Cl-ASSISTED OMVPE AT ATMOSPHERIC PRESSURE

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Abstract

Selective epitaxy of GaAs by OMCVD is generally obtained at low pressure, when the diffusion length of the active specie over the dielectric mask is large enough. Another way is to use an organochloride as a precursor, which suppress the deposition over the dielectric. This method is also used at reduced pressure.

In this work, we have obtained selective area epitaxy of GaAs and GaAlAs for a wide range of aluminium composition by adding a controlled flow of AsCl₃ during a conventional OMVPE growth at atmospheric pressure. This method is called Cl-assisted OMVPE. When no AsCl₃ is used, a finely structured polycrystal is deposited on the mask. When AsCl₃ is introduced into the reactor, with otherwise the same growth conditions, complete selectivity was obtained over a 100 µm wide Si₃N₄. We have studied the influence of the growth temperature, the TMG/AsCl₃ and the AsH₃/TMG ratios on the growth selectivity.

The selective epitaxy is attributed to the formation of HCl, then to the adsorption of HCl on the mask, blocking the polycrystal deposition. On the GaAs openings, two reactions are competing, etching:



and growth:



By varying the TMG/AsCl₃ ratio, it is possible to change the balance between these two reactions, and we have observed an increase of the growth rate in the openings with increasing the TMG/AsCl₃ ratio.

We have also studied the selective growth of GaAlAs for different aluminium compositions. By adjusting the ratio (TMG+TMA)/AsCl₃, selective growth of GaAlAs for different composition was obtained. We have also investigated the evolution of the limiting planes of the selectively grown ridges with different growth conditions. Finally, on a selectively grown GaAs/GaAlAs double heterostructure, room temperature photoluminescence topography was performed.

PHOTOLUMINESCENCE MICROSCOPY INVESTIGATION OF LATTICE
DEFECTS IN HETEROSTRUCTURES GROWN BY METALORGANIC
VAPOUR PHASE EPITAXY AND MOLECULAR BEAM EPITAXY

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An improved photoluminescence microscopy technique will be introduced. Due to its high resolution it has been successfully used to investigate in detail non-radiative defects and crystal imperfections in different AlGaAs/GaAs und InGaAs/GaAs heterostructures. The creation and gradual modification of lattice defects in different layers can be observed very clearly. The technique is nondestructive and fast, allowing routine wafer analysis during processing procedures.

Results on different lattice matched AlGaAs/GaAs and pseudomorphic InGaAs/GaAs quantum well (QW) structures grown by metalorganic vapour phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) will be presented. In a MOVPE grown AlGaAs QW structure dislocations from the LEC GaAs substrate are found to propagate through a lattice matched superlattice (SL) into the GaAs buffer but are blocked by a 90 nm thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer. In a sample of the same structure but grown by MBE dislocations from the buffer are partly blocked by the SL buffer but propagate through the 90 nm thick AlGaAs layer into the following QW layers. Small scale, laterally homogeneous fluctuations of QW luminescence indicate that the interface quality can also be characterized microscopically.

In a MOVPE grown pseudomorphic $\text{In}_x\text{Ga}_{1-x}\text{As}$ QW layer below critical thickness threading dislocations from the LEC GaAs substrate were observed to act as nucleation centers for misfit dislocations in the InGaAs QW layer. With increasing thickness or In content, a network of dislocations is formed with a number of different orientations but no unequivocal directional preference. The patterns are distinctly different from MBE grown layers which exhibit a regular orthogonal dislocation grid parallel $\langle 110 \rangle$.

THURSDAY, MAY 21, 1992
(8:30 -10:45)

Session n° 4 : Growth, and characterization of compound semiconductors

Chairman : A. Winnacker, University of Erlangen, Germany.

8:30 - 9:00 INVITED LECTURE

"Crystallographic and Chemical Inhomogeneities in Compound Semiconductor Substrates and their Relevance to Device Performance"
J. Weyher, MASPEC, Parma, Italy

9:00 - 9:30 INVITED LECTURE

"Two Direct Analytical Methods for Semiconductor Materials Assessment"
A. Huber and C. Grattepain, Thomson LCR, Orsay, France

9:30 - 9:45

Photoluminescence and Photoacoustic Investigation of Residual Defects in Semi-Insulating LEC GaAs. O. Ka¹⁾, O. Oda²⁾, Y. Makita¹⁾, A. Yamada¹⁾, ¹⁾ Electrotechnical Laboratory, Tsukuba, Japan, ²⁾ Nippon Mining Co., Tsukuba, Japan.

9:45 - 10:00

SIRM and TEM Studies of Inhomogeneities in S-Doped InP. N.Y. Jin¹⁾, G.R. Booker¹⁾, I.R. Grant²⁾, ¹⁾ Oxford University, Oxford, UK, ²⁾ MCP Wafer Technology Limited, Milton Keynes, UK.

10:00 - 10:15

On the Distribution of Fe in Semi-Insulating InP. R. Treichler¹⁾, J. Völkl²⁾, Th. Vetter²⁾, G. Wittmann²⁾, A. Winnacker³⁾, ¹⁾ Siemens Corporate Research and Development, Munchen, Germany, ²⁾ Siemens Corporate Research and Development, Erlangen, Germany, ³⁾ University of Erlangen, Erlangen, Germany.

10:15 - 10:30

Recent Advance in the Assessment of GaAs Substrate Quality by Scanning Photoluminescence. K. Schohe¹⁾, F. Krafft²⁾, C. Kingelhöfer²⁾, M. Garrigues¹⁾, S.K. Krawczyk²⁾, J. Weyher³⁾, ¹⁾ SCANTEK, Ecully, France, ²⁾ Ecole Centrale de Lyon, Ecully, France, ³⁾ MASPEC, Parma, Italy.

10:30 - 10:45

Electrical Properties of Thermally Annealed Fe-Doped Semi-Insulating InP. A. Kalboussi¹⁾, G. Marrakchi¹⁾, G. Guillot¹⁾, K. Kainosho²⁾, O. Oda²⁾, ¹⁾ INSA de Lyon, Villeurbanne, France, ²⁾ Nippon Mining Company, Saitama, Japan.

Crystallographic and chemical inhomogeneities in compound semiconductor substrates and their relevance to device performance.

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A wide range of crystallographic and chemical inhomogeneities are inherently formed during bulk growth of III-V compound semiconductors. A classification of the different types of inhomogeneities occurring in commercially available substrates will be presented together with a description of their origin. Taking GaAs as a representative example, the importance of defects for performance of devices such as FETs, solar cells, LEDs and lasers will be discussed. The problem of proper standard specifications which are given by producers of substrates will be considered.

TWO DIRECT ANALYTICAL METHODS FOR SEMICONDUCTOR MATERIALS ASSESSMENT.

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ABSTRACT

The basic parameters which determine the electronic materials quality are : crystal perfection and chemical composition (doping profile, low "parasitic" impurity concentration). The most often used electrical, x-ray and photoluminescence measurements give indispensable though "indirect" information about material quality. It is therefore necessary for device materials producers to have at their disposal "direct" methods for fast determination of crystal lattice perfection and chemical composition problems and give the concrete solution, for the improvement of materials.

In this exposition we will present some new experimental results concerning III-V compounds material assessment by direct methods : 1) etching technique on chemically angle polished samples (ETOCAPS) for lattice perfection observation and 2) secondary ion mass spectrometry (SIMS) for chemical analysis. The short description of methods will be followed by a presentation of some technologically important results.

PHOTOLUMINESCENCE AND PHOTOACOUSTIC INVESTIGATION OF
RESIDUAL DEFECTS IN SEMI-INSULATING LEC GaAs

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Post-growth annealings are usually carried out to reduce the defect density in Czochralski-grown Si GaAs, which are known to affect the device properties. Ingot annealing, single- (IA) or multi-step (MIA) have shown their inability to simultaneously lead to low defect density and good uniformity of the electrical properties. Thus, single- and multi-step wafer-annealing (WA and MWA, respectively) have been developed in order to fulfill the above requirements.

A systematic study of crystals submitted to the different annealing methods has been carried out, using photoluminescence (PL) spectroscopy. Above band-gap excited PL spectra display well resolved excitonic lines for the different crystals but the IA one. The neutral acceptor-bound exciton, A^0X , appears as a doublet usually displayed by high quality epitaxial layers, with a full width at half maximum (FWHM) as low as 0.15 meV. The spectra also definitely show the improvement of the crystalline quality of wafer-annealed samples through the absence of the additional recombination paths displayed by ingot-annealed samples, especially the MIA. The latter presents a very sharp line at 1.510 eV, possibly related to a new band at 1.482 eV, as suggested by resonant excitation PL measurements. In both IA and MIA, a deep defect-induced band appears around 1.447 eV, with the resolution of two transitions, ascribed to the electron-acceptor (e, A^0), and donor-acceptor (D^0, A^0) pair transitions of an acceptor-like deep defect.

The 1.482 eV band is asserted to be the low temperature recombination path, corresponding to the peak occurring at 1.39 eV for the room temperature photoacoustic (PA) measurements. The PA intensity of the 1.39 eV peak is shown to be a direct estimation of the arsenic microdefect density as evaluated by AB etching, therefore giving a simple method for an evaluation of the microdefect density.

Besides the above differences following wafer- and ingot-annealing, selective excitation of the donor-acceptor pair luminescence (SPL) involving shallow acceptors reveal that for comparable carbon concentrations, wafer-annealed crystals present a much lower level for the other usual acceptor impurities in Czochralski-grown GaAs, i.e. Zn and Si. The concentration of the latters, estimated from the SPL measurements, appears to be around 10^{13} cm^{-3} or below, a result of high technological interest for MESFET device applications using these crystals as substrates.

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SIRM and TEM Studies of Inhomogeneities in S-Doped InP

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Scanning infra-red microscopy (SIRM) has been used to characterize defects in InP wafers from LEC grown S-doped InP ingots. The light from a $1.3\mu\text{m}$ wavelength semiconductor laser is focused into a spot $\sim 2\mu\text{m}$ across within the wafer, which is mechanically raster-scanned. The signals from the photodetector which collects either the transmitted or scattered light are stored and displayed to give bright-field (BF) or dark-field (DF) images respectively. Individual particles down to 30nm can be imaged. In addition to the standard transmission mode, the cross-polarized mode is also employed.

The main inhomogeneities observed in InP wafers by SIRM are linear features, interior particles, surface particles and alternating bright-dark bands.

Since the contrast of an image in the standard mode arises mainly from the scattering of the light by particles, the observation of continuous linear features indicates that they are dislocations or narrow planar defects decorated by small precipitate particles. In some cases closely spaced particles of low contrast along these lines are resolved at higher magnifications. When crossed polariser and analyser are used, the local strain field associated with a dislocation gives rise to its contrast. Additional dislocations are revealed in this mode, mainly in the wafers with lower S-dopant concentrations and high dislocation densities. These latter dislocations are not decorated with precipitate particles and can not be imaged in the standard BF mode and DF mode. In general, the dislocation density is $\sim 10^3\text{cm}^{-2}$ and depends on the location in the ingot. It is lower in the wafers close to the tail-end than the seed-end, as well as in the center of a wafer than near the major flat. The density increases with the reduction of S-dopant concentration, and after post-growth heat treatment.

Small particles not associated with crystallographic defects are present in some wafers. Wafers originally with no observable particles sometimes exhibit a high density (10^7 to 10^8cm^{-3}) of small particles after annealing. Particles in or close to the surfaces are sometimes observed, which are considered to be associated with the wafer polishing process. They are virtually eliminated when a careful polishing process is employed.

Alternating bright and dark bands are observed in most wafers with spacing $150\text{--}450\mu\text{m}$ (dark to dark), and are often more pronounced near the major flat than the centre. Bands that appeared dark in BF are bright in DF, and vice-versa. The results suggest that they are dopant striations.

Detailed TEM (transmission electron microscopy) has been performed on selected wafers. Dislocations and planar defects, such as stacking faults and microtwins, are observed often with decorating point defect aggregates and precipitate particles of 2-20nm. In the wafer of lower S-dopant concentration, more dislocations are undecorated. Isolated particles 5-100nm across, sometimes surrounded by dislocation segments in many slip systems, are also observed. The results from SIRM and TEM correlate well with each other. Further study on the nature of the different types of dislocations, interior particles and the bands, in combination with other techniques, is in process.

The financial support of SERC is gratefully acknowledged. Thanks are due to Mr. Z.J. Laczik and Mr. P. Torok for help with some of the work.

On the distribution of Fe in semi-insulating InP

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Semi-insulating InP is the basic material for integrated electronic circuits for long range data communication. Electrical homogeneity of the substrate material is an essential requirement for the technology. Generally the material is made semi-insulating by compensating residual shallow donors by the deep acceptor Fe. So the electrical inhomogeneities can either be caused by inhomogeneities in the distribution of the shallow impurities, or by inhomogeneities in the distribution of the Fe-acceptor in the crystal. Thus, in order to understand the origin of electrical inhomogeneities of the material, the distribution of both partners in this compensation process has to be determined. Because -according to the general compensation model- the concentration of the residual donors equals the concentration of Fe^{2+} , a measurement of the distribution of Fe in both its charge states, Fe^{2+} and Fe^{3+} , will reveal both: the distribution of the shallow donors as well as the total Fe-distribution in the wafers. The distribution of Fe in its Fe^{2+} - and its Fe^{3+} -state can be measured by optical absorption¹⁾ in the below-bandgap-region. Results on typical Czochralski wafers will be presented and the limitations and problems of the method will be discussed.

A second kind of inhomogeneities inherent in the crystal-pulling process are striations. Striations in wafers cannot be seen in absorption. So different methods have to be applied. Striations were investigated by photoluminescence mapping. In order to understand the origin of the photoluminescence contrast the wafers were at the same time investigated by locally resolved SIMS measurements²⁾. Correlations were established between the photoluminescence images and the impurity distributions found by SIMS.

The main results on both types of inhomogeneities (the ones seen in absorption and the striations) can be summarized as follows: In the LEC-wafers studied by us the main source of inhomogeneity seems to be the distribution of Fe. In comparison with Fe the residual shallow donors seem fairly homogeneously distributed. This result can be understood as a consequence of the small segregation coefficient of Fe. In this way it points towards an inherent problem of the present technology of semi-insulating InP based on Fe-doping, and pushes the interest of new ones³⁾.

1) W. Meier, H.Ch. Alt, Th. Vetter, J. Völkl and A. Winnacker, *Semicond. Sci. Technol.* 6 (1991) 297

2) Th. Vetter, R. Treichler, and A. Winnacker, *Semicond. Sci. Technol.* 7 (1992) 150

3) G. Hirt, D. Hofmann, F. Mosel, N. Schäfer and G. Müller, *J. Electronic Mat.* 20(12) 1991 1065, and references therein.

Recent Advance in the Assessment of GaAs Substrate Quality by Scanning Photoluminescence

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The purpose of this contribution is to demonstrate recent progress in the application of scanning photoluminescence (SPL) for the assessment of GaAs crystals. Experimental results reported here have been obtained with a SCAT IMAGEUR (scanning photoluminescence system from SCANTEK, France) on semi-insulating and doped GaAs substrates from various suppliers.

Technical progress

Progress in the design of the optics and improvements of the photodetection allow measurements of the room-temperature PL signal from semi-insulating GaAs with an acquisition time of less than 1ms. Consequently, rapid measurements can be performed with a resolution sufficiently high to reveal the cellular structure of the dislocation distribution on entire 2" or even 4" wafers (Fig. 1). On the other hand, we have developed advanced procedures which consist of sampling the wafer area with small zones scanned at high resolution (<1µm). This high resolution is necessary to reveal details such as individual dislocations, related impurity atmospheres and precipitates. In this manner we obtain meaningful information on the substrate quality.

Progress in interpretation of SPL images

We demonstrate a tight correlation between SPL images and (scanning) differential interference contrast (DIC) optical images obtained on the same area of GaAs samples after photoetching (DSL method). In addition, spatial non-uniformities of the PL signal were quantitatively correlated with the local etching rate. It appears clearly, that high resolution SPL images provide roughly the same information as DSL etching. In particular, the morphology of SPL images allows the identification of different types of dislocations, precipitates and doping striations (Fig. 2).

Quantitative data analysis

It has been shown recently [1], that the contrast of the PL intensity across cell boundaries is tightly correlated with the dispersion of the resistivity of the substrate. For routine applications we have developed statistical data treatment procedures, which allow wafer scale probing of the local electronic uniformity and the comparison of different wafers. Such analysis is particularly interesting for the optimization of ingot annealing processes and for substrate quality checking for MESFET technology based on direct ion implantation.

[1] M. Baumgartner, G. Nagel and K. Löhnert, Proceed. 6th Conf. Semi-Ins. III-V mater., Adam Hilger, Bristol (1990), p. 225

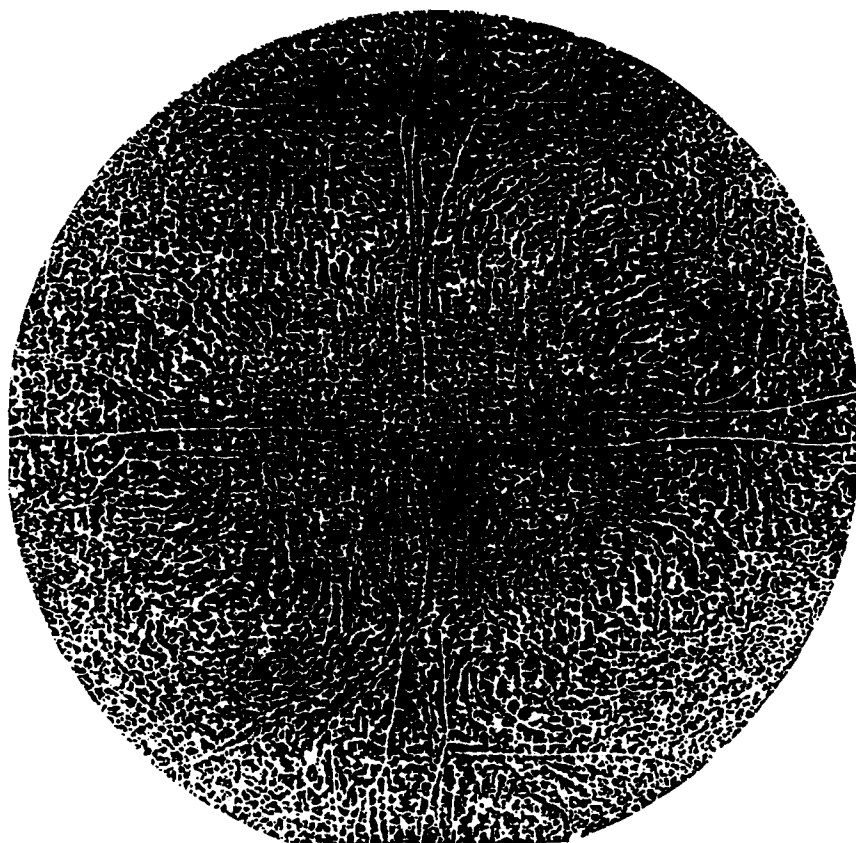


Fig. 1 : SPL image of a commercial 2" GaAs-S.I. wafer, LEC, $\langle 100 \rangle$; scanned area is 60mm in square with 1000x1000 measurement points



Fig. 2 : Comparison of SPL and DSL images (insert) of a Si-doped GaAs sample. The PL image (400x400 points, 2mm square) was obtained before, the DIC image after DSL etching. Both techniques reveal doping striations as well as grown-in dislocations which moved during cooling.

Electrical properties of thermally annealed Fe-doped semi-insulating InP

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Optoelectronic integrated circuits based on InP need the availability of low defect semi insulating (SI) InP substrates doped with Fe with a high resistivity. During the processing of devices the InP substrate is usually subjected to high temperature annealing around 700°C for the growth of epitaxial layers or the electrical activation of implants. These thermal treatments induce two problems: the thermal stability of the Fe acceptor trap and the possible formation of new electrically active defects. As a consequence the study of the thermal stability of SI InP substrates and associated deep levels is highly important.

We present the results of Photo-Induced Current Transient Spectroscopy (PICTS) on SI Fe doped InP subjected to high temperature thermal annealing. LEC Fe-doped InP wafers have been capped by sputtered SiN_x films and then annealed for 15 min at temperatures between 663°C and 820°C in an infrared image furnace. After annealing the SiN_x cap was removed by HF etching and two ohmic contacts were deposited front face. The presence of deep levels has been investigated by means of PICTS using 1.3 eV incident light produced by an infrared LED as an excitation source.

On an unannealed reference sample, the only deep trap detected by PICTS is the Fe^{2+/3+} acceptor level at E_c - 0.63 eV. On annealed samples we detected the formation of four deep traps at the following energies : 0.15, 0.25, 0.41 and 0.53 eV named respectively T1 to T4. Resistivity measurements performed on the same samples have shown a decrease of resistivity as a function of annealing temperature which is indicative of donor formation. SIMS analysis performed on annealed samples have indicated the intrinsic nature of the donor levels created. In conclusion, we have shown the formation of thermal donors in Fe-doped wafers for thermal anneal at high temperature under SiN_x capping conditions leading to a deterioration of the electrical properties.

THURSDAY, MAY 21, 1992
(11:00 - 12:00)

Session n° 5 : New frontiers

Chairman : J.P. Fillard, Université de Montpellier II, France

11:00 - 11.30 INVITED LECTURE

"From Micro- to Nanoelectronics : New Technology Requirements"
M. Van Rossum, IMEC, Heverlee, Belgium

11.30 -12:00 INVITED LECTURE

"Evaluation of III-V Epitaxial Layers Grown by Atomic Layer Epitaxy" M. Ozeki and
A. Shibatomi, Fujitsu Laboratories Ltd., Atsugi, Japan

FROM MICRO- TO NANOELECTRONICS : NEW TECHNOLOGY REQUIREMENTS

M. Van Rossum
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The field of nano-electronics has recently evolved into a major area of investigation. This explosive growth has been triggered by the concurrence of theoretical and technological developments which have dramatically increased our ability to build very small devices and to predict their operation. In this presentation, the main technological requirements for research on nanodevices will be identified, both from the fabrication and from the characterization viewpoint. On the fabrication side, the basic issue is the improvement of the process control for lateral patterning. Simple structures can be prepared by electron beam direct write and metal lift-off; this process, when combined with advanced lithographic techniques, is able to define patterns down to horizontal dimensions of a few nm. For more elaborate device structures, horizontal patterns can be transferred into the substrate by reactive ion etching or focused ion beams. However, these techniques inevitably introduce damage in the substrate material, which must be carefully characterized e.g. by optical spectroscopy or by DLTS. Most devices also require the integration of electrical contacts and interconnects, which can be a major source of resolution loss at very small dimensions. The solution here lies in the development of new metallurgical approaches which allow a better control of the contact morphology. Another difficulty is the combination of several processing steps on a non-planar topology. On the other hand, some combinations of this kind (e.g. epitaxial growth on patterned substrates) can be used as an additional tool for nanostructure fabrication. Three-dimensional structural characterization of these non-planar elements is an important requisite for process control, but is still difficult to achieve. Recent work has demonstrated the usefulness of STM or AFM for this purpose, as well as of some specialized laser probing techniques. Finally, new methods must be developed for the electrical characterization of nanodevices, due to their very short switching times. In some cases, measurement of electron transit times can be performed in a time-resolved mode with the help of femtosecond laser pulses. To illustrate the use of some of the techniques mentioned above, we will present recent work on the fabrication and characterization of nanoscale field-effect transistors.

Evaluation of III-V Epitaxial Layers Grown by Atomic Layer Epitaxy

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The current interest in quantum-effect devices has led to improved crystal growth controllable at the atomic level. Atomic layer epitaxy (ALE) has received considerable attention as a novel approach to crystal growth, with potential advantages over conventional epitaxies. ALE has self-limiting mechanism, in which epitaxial growth automatically stops exactly at one monolayer. This distinguishes ALE from other epitaxial techniques and enables the layer thickness be completely controlled at the atomic level.

Epitaxial layers of an extremely uniform thickness are grown by ALE on large substrates with little fluctuation in thickness. As an ideal two-dimensional growth process, ALE has the large potential for selectively growing fine patterns, heteroepitaxy over a largely lattice-mismatched substrate and the growth of a layer with a completely flat and defect-free surface.

Optical and electrical measurements for ALE grown epitaxial layers show unique properties in impurity and defect incorporations, which are important for device fabrication processes.

ALE makes it possible to control the layer thickness at the atomic level even in heterostructures. When film thickness is decreased to one or two monolayers, new physical and chemical features appear which cannot be explained by the energy band structures of the respective materials composing the heterosystem. These short-period superlattices are considered to be "artificial material" and may offer the possibility of designing materials with specific physical and chemical properties by combining different thin films.

The strained-layered superlattices $(\text{GaAs})_m(\text{GaP})_n$ grown by ALE has indicated the appearance of new energy-band structures. Optical studies by photoluminescence and reflectance measurements showed that the monolayer superlattice $(\text{GaAs})_1(\text{GaP})_1$ grown on GaAs substrate has an energy structure of direct band gap, differing from that of $\text{GaAs}_{0.5}\text{P}_{0.5}$ alloy. Structural and defect analyses by x-ray, transmission electron microscopy and Raman scattering measurements have revealed unique properties in these strained layer superlattices.

FRIDAY, MAY 22, 1992
(8:45 - 9:45)

Session n° 6 : Towards technology improvements

Chairman : P. Viktorovitch, Ecole Centrale de Lyon, Ecully, France

8:45 - 9:15 INVITED LECTURE

"Concepts of Ultra-Stable Metal Contacts and their Evaluation"
H.L. Hartnagel, THD, Darmstadt, Germany

9:15 - 9:45 INVITED LECTURE

"UVCVD Dielectric Deposition for InP-Based Optoelectronic Devices"
G. Post, Y. Le Bellego, J.L. Courant, A. Scavennec, CNET Bagneux, France

Concepts of ultra-stable Metal Contacts and their Evaluation

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Metal contacts represent an essential part of all devices and IC's on compound semiconductors. The new developments of heterojunction technology and nanometric structuring have to consider therefore also the relevant developments of metal electrodes.

The well proven schemes are diffusion barriers, particularly to prevent outdiffusion and loss of the volatile components such as P or As, adhesion layers such as Ni or Cr, and doping layers, such as Zn or Ge. These aspects have received a great deal of attention recently, particularly in view of the new structural requirements. There are metallization efforts described recently which are based on single-crystal, lattice-matched metallic films grown either in UHV-MBE or by solid-phase thin-film epitaxy. For minimum damage of the interface as evaluated also by the resulting noise behaviour, electrolytic deposition techniques are often successfully applied. now.

The evaluation techniques use the traditional transmission line, the Kelvin structure or very simple approximative approaches, where good-contact results can be explained nowadays very successfully. However, for nanometric requirements, the questions of clustering of initial metal deposition, of lift-off accuracy with multi-layers and of local stress fields are some of the important points which have been evaluated by scanning tunnelling microscopy, by SEM, by TEM and other related techniques.

UVCVD DIELECTRIC DEPOSITION FOR InP-BASED OPTOELECTRONIC DEVICES

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Integrated optoelectronics for fibre optics communications relies on chemically reactive materials: InP and epilayers of AlInAs, GaInAs etc. Their successful passivation by photochemically deposited dielectrics will be presented. UV-assisted CVD produces high quality silicon nitride and silicon dioxide layers at low substrate temperature and without energetic ion bombardment, by contrast to thermally or plasma activated CVD. InGaAs pin and avalanche photodiodes will illustrate the application of silicon nitride passivation on the receiver side, InP MISFETs monolithically integrated with BRS GaInAsP/InP lasers stand for the use of UVCVD SiO₂ on the transmitter side.

Processing: Reactant gas mixtures are diluted silane and nitrous oxide for the CVD of SiO₂, pure silane and ammonia for silicon nitride deposition. Both processes use indirect activation: the gas phase contains about 0.1 % of mercury vapour which absorbs 254 nm UV light, and reactive atoms and radicals result from collision with excited Hg atoms.

For silicon dioxide, we chose a substrate temperature of 180 °C. The infrared spectra of films show the signature of by-products: for small N₂O/silane flow ratios, SiH stretching vibrations appear, for very high values, we found N=O groups. The optimum flow ratio yields a film composed of SiO₂, bound H₂O molecules, and SiOH groups. Flash annealing at 500 °C is sufficient to desorb all the hydrogen as H₂O vapour: however, the remaining dielectric has a very large defect concentration. In view of InP applications, a low temperature dehydration bake has been studied. After heat treatment at 300 °C in a dry oxygen ambient, the structures are stable (hysteresis about 1.5 V for all voltage sweep rates) and have a fast interface state density of 10¹² cm⁻²eV⁻¹. Trap densities closer to 10¹¹ cm⁻²eV⁻¹ result from 200 °C annealing, with somewhat more hysteresis and moisture in the films.

The UVCVD of silicon nitride (from SiH₄ and NH₃) was done at 240 °C. In-situ UV treatment in pure NH₃ has been applied in order to reduce surface oxides. This led to good SiN/ GaInAs interfaces: they qualify well as masks for selective zinc diffusion; the C-V hysteresis and the interface trap density remain low after such a heat treatment. However, preliminary experiments on undoped AlInAs indicate that this surface reacts destructively in the SiH₄/NH₃ ambient.

Pin structures for OEICs have been investigated, starting from N⁺/N⁻ InGaAs layers grown by MBE on semi-insulating InP. In the first type, zinc is diffused into the whole surface to create the p⁺n junction, followed by mesa etching and eventually UVCVD nitride deposition to protect the junction at the diode edge. The second structure involves selective Zn diffusion in the windows of a UVCVD silicon nitride mask. Dark currents have been compared between bare "type 1" pin diodes, measured under nitrogen after oxide removal, and SiN_x passivated junctions. The optimized dielectric deposition process does not alter the static characteristics of the pin diode whose dark current is 30 nA at room temperature (generation current) and 1.25 μA at 125 °C (diffusion limited current), with excellent stability of the passivated junctions. For selectively diffused "type 2" junctions as well, the UVCVD nitride masked devices had less leakage current than comparable diodes with PECVD masks.

Avalanche photodiodes: Separate Absorption, Grading, Multiplication layer structures were grown by MBE. These have a series of three pn junctions which have been nitride passivated.

The top p⁺n contact is biased under conditions similar to those of pin diodes, the same planar UVCVD mask and selective zinc diffusion technology has been used there. The GaInAs absorption layer joins a Be doped AlGaInAs grading layer at the next np junction. The last pn junction is located at the AlInAs/GaInAs multiquantum well avalanche region where the field is at its maximum and where the high aluminium concentration contributes to surface reactivity. Our SAGM diodes have been successfully passivated with a second SiN_x deposition after mesa etching and de-oxidizing.

The avalanche layer is a multiquantum well formed by 10 periods of AlInAs/GaInAs. From impulse response measurements, we obtained a value of 50 GHz for the gain-bandwidth product. The excess noise factor plotted against the electron multiplication agrees well with theory for electron-over-hole ionisation rate ratios equal to 10 (M < 8). Pure electron injection is achieved for both front and back side illumination.

InP MISFETs were made using ion implantation (contact and channel, enhancement and depletion modes) and UVCVD SiO₂ gate insulator. They provide a high power density for amplification at 10 GHz, to the advantage of the monolithic integration of a pair of MISFETs with a 1300 nm BRS laser diode. MISFET processing could be made fully compatible with the laser fabrication: no degradation of the epitaxial layers during the annealing of FET implantations. Laser diodes with a threshold current of 10 mA have been assembled with 1.5 μm gate FETs of 80 mS/mm (SiO₂ dielectric 70 nm). The module features a light power efficiency of 12 mW/V and operates up to 10 Gbit/s, allowing to reduce the electric modulation power by 6 dB with respect to a single, series-resistance matched laser diode.

In order to prove that - in baseband photodetection applications - the noise properties are in favour of InP channel FETs compared to GaInAs ones, we measured hybrid pin-MISFET photoreceiver front ends. The input noise current density at 5 MHz was only 0.5 pA/ Hz^{1/2}, and receiver sensitivities, evaluated as -42.8 dBm at 140 Mbit/s and -37.5 dBm at 560 Mbit/s, are among the best values reported for pin-FET hybrids.

Acknowledgment: Part of the work has been supported by the ESPRIT programme.

FRIDAY, MAY 22, 1992
(13.30 - 16:00)

Session n° 7 : Advanced material and process characterization techniques

Chairman : C. Frigeri, MASPEC, Parma, Italy

13:30 - 13:45

Stability of GaAs MESFET's Gate Contact Studies by High Resolution TEM. N. Labat¹⁾, Y. Danto¹⁾, B. Plano¹⁾, M. Chambon¹⁾, J.M. Dumas²⁾, ¹⁾ Université de Bordeaux I, Talence, France, ²⁾ CNET, Lannion, France.

13:45 - 14:00

Investigation of Photoluminescence Mapping and Transients in AlGaAs/GaAs Heteroface Solar Cells. A. Ehrhardt, W. Wetzling, S. Cardona, Fraunhofer-ISE, Freiburg, Germany.

14:00 - 14:15

Photoluminescence Surface State Spectroscopy for In-Situ Semiconductor Surface and Processing Characterization. H. Hasegawa, T. Saitoh, K. Numata, T. Sawada, Hokkaido University, Sapporo, Japan.

14:15 - 14:30

Studies of GaAs Surfaces by Scanning Tunneling Induced Photon Emission. M. Bischoff, C. Sprössler, H. Pagnia, R. Richter, J. Horn, H.L. Hartnagel, Technical University of Darmstadt, Darmstadt, Germany.

14:30 - 14:45

Gated Photoluminescence and Raman Spectroscopy Analysis of InP Interfaces. D.L. Lile, M. Ochiai, R. Iyer, Colorado State University, Fort Collins, USA.

14:45 - 15:00

Opto-Electronic Modulation Spectroscopy (OEMS) - a New Tool for Device Investigations. M. Di Marco, Q. Wang, J.G. Swanson, King's College, London, U.K.

15:00 - 15:15

A Study of Light Intensities Scattered from Defects in an In - doped LEC GaAs Crystals as a Function of Wavelength and Intensity of Bias Light Superposed on the Defects. K. Sakai, R. Hashimoto, T. Ogawa, Gakushuin University, Tokyo, Japan.

15:15 - 15:30

Optical NDT for Evaluation of Microprecipitates in Semiconductor Materials and Devices. J.P. Fillard, Université de Montpellier II, Montpellier, France.

15:30 - 15:45

Optical Characterization of Si Wafers for ULSI. T. Ogawa¹⁾, T. Lu²⁾, K. Toyoda²⁾, N. Nango³⁾, ¹⁾ Gakushuin University, Tokyo, Japan, ²⁾ Institut of Physical & Chemical Research, Saitama, Japan, ³⁾ Ratoc Systems Engineering Co., Tokyo, Japan.

15:45 - 16:00

The Effects of Probe Power Density on the Spatially Resolved Room Temperature Photoluminescence of Optoelectronic Epitaxial Structures. C.J.L. Moore, J. Hennessy, Waterloo Scientific Inc, Waterloo, Ontario, Canada.

16:00 END OF THE WORKSHOP

**Stability of GaAs MESFET's gate contact studied by high resolution TEM
(Transmission Electron Microscopy)**

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Accurate cross-sectional views of GaAs devices are useful for failure analysis and process evaluation. Transmission electron microscopy is a technique commonly used for semiconductor material and interface studies [1] and a few papers are related to the correlation of observations on GaAs devices with the electrical parasitic effects [2, 3].

In the present work, a technique to prepare thin sections of specifically desired regions [4] within GaAs components for TEM observation is proposed.

This sample preparation technique has been successfully used to study the recessed gate contact of GaAs MESFETs. Correlations have been found between the gate metallisation - active layer interface properties and the evolution of the I-V characteristics of the gate-source Schottky diode.

The studied devices presented high values of the gate leakage current. This excess current is strongly dependent on the curvature radius of the gate edge and the gate recess and on the electric field in this region. A TEM observation has clearly shown the presence of structural defects inherent to the fabrication process and particularly to a narrow and abrupt gate recess etched in the preencapsulated SiN substrate. From the GaAs surface left unprotected at the periphery of the gate recess, conductive paths located in the access regions (figure 1) are supposed to be responsible for this excess leakage current [5].

The forward biased Log(I)-V characteristic of the gate diode presented an abnormal N-shape. This behaviour has been attributed to a non uniform Schottky barrier height resulting from the properties of the gate metallisation-substrate interface. The model of a multi-phase contact is correlated with high resolution TEM observations. An intermediate amorphous layer (thickness 5 nm) composed of non stoichiometric titanium oxide compounds has been detected at the interface (figure 2).

We have briefly reported on the implications of the TEM observed structure of the MESFET gate contact on the electrical characteristics of this device.

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'An investigation of high temperature degradation of Ti/Pt/Au Schottky contacts to GaAs FETs using TEM technique'
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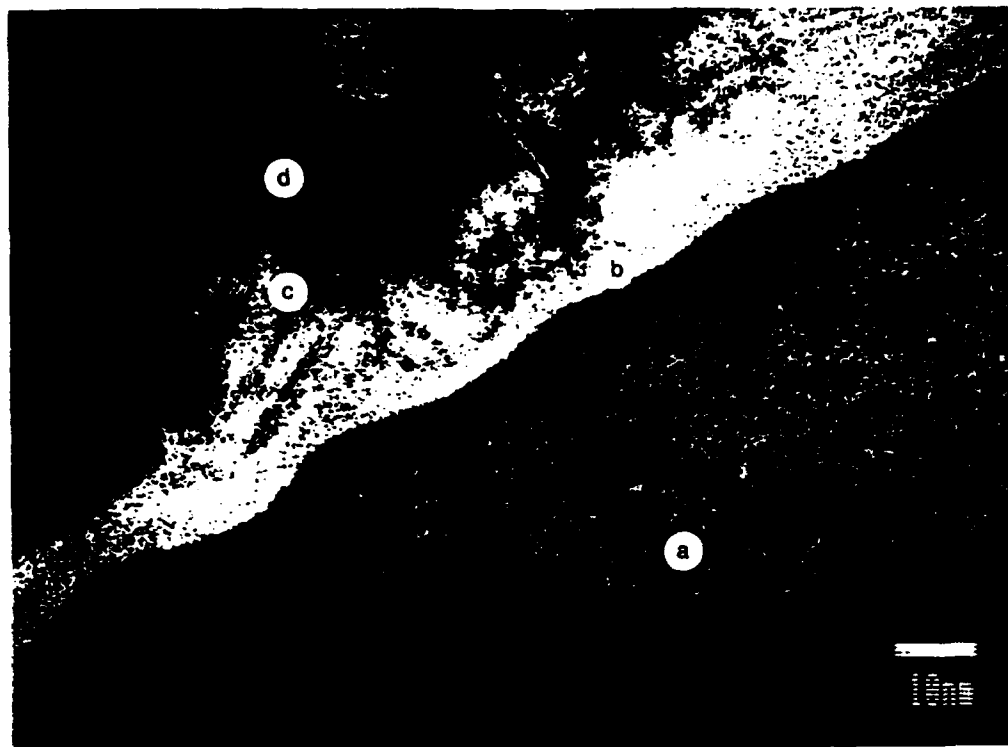


Figure 1 : TEM image of the gate metallisation - GaAs active layer interface
a : n-GaAs active layer - b : Interface amorphous layer - c : TiPt grains - d : "Moiré" effects

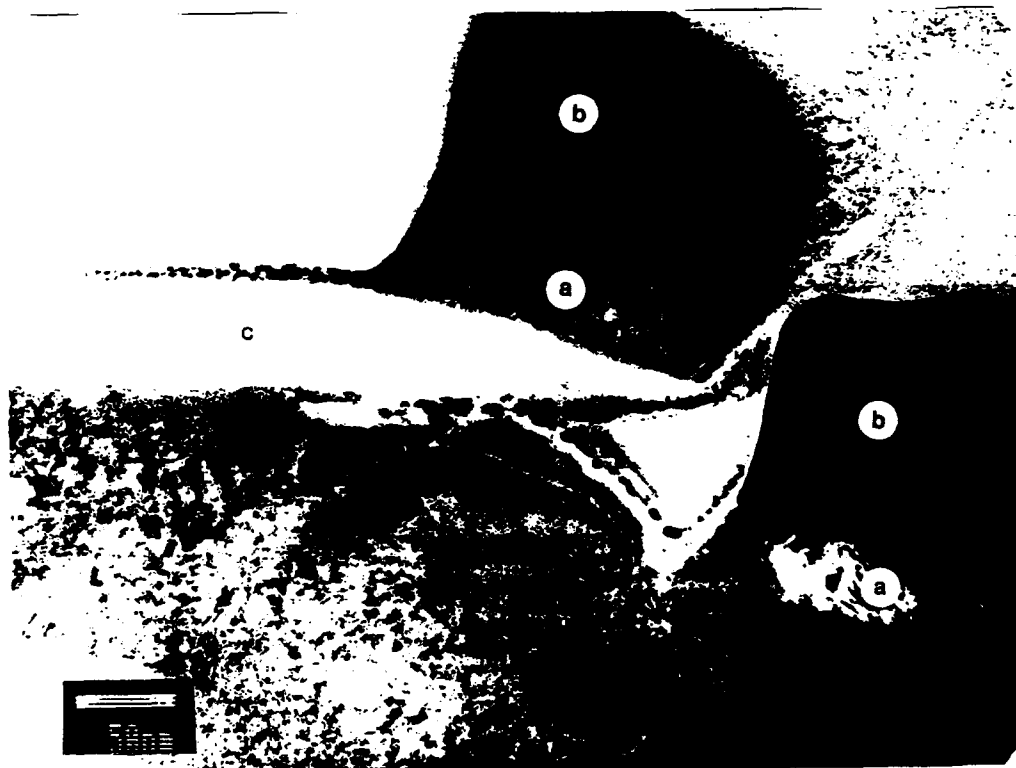


Figure 2 : TEM image of the gate contact at the periphery of the recess :
a - TiPtAu polycrystalline layer ; b - TiPtAu (gold rich gate metallisation layer ;
c - RF sputtered Si_3N_4 layer.

INVESTIGATION OF PHOTOLUMINESCENCE MAPPING AND TRANSIENTS IN AlGaAs/GaAs HETEROFACE SOLAR CELLS

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An optical system has been set up that allows to record photoluminescence mapping (PLM) and photoluminescence transients (PLT) while the sample is at the same position. The spatial resolution is $5\text{ }\mu\text{m}$ and the time resolution is 20 psec. The technique of combined PLM and PLT measurements has been applied to the study of $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ heteroface solar cells.

The PLM technique reveals spatial inhomogeneities of the emitter or the heterowindow layer thus allowing an evaluation of the LPE or MBE epitaxial process in a very direct and demonstrative but only qualitative way. After recording the color coded PLM images the PLT are recorded at various points of interest on the surface. This is performed by means of a pulsed dye laser system and an optical sampling oscilloscope that are integrated in the system.

The experimentally recorded multiexponential PL transients can be fit to a theory that is based on an analytical solution for the time dependent PL intensity. This solution has been derived by using a Fourier transform method. The fit parameters are device parameters relevant for the description of the solar cells, namely bulk and surface recombination, minority carrier diffusion coefficient and thickness of the layers. These parameters can thus be derived quantitatively by the fitting procedure.

In the paper examples of PL maps and PL transients recorded on LPE layers, MBE layers and processed solar cells are given.:

- There is a clear correlation of PLM, PLT and short circuit current of solar cells which is due to the dominant influence of the heterowindow-to-GaAs interface on the surface recombination.
- In the LPE process the time of contact between melt and substrate determines not only the thickness of the emitter layer but influences also the bulk and surface quality, i.e. the longer the contact time the lower the recombination.
- MBE layers of GaAs on Si substrates were also investigated. The PLT allows an order of magnitude determination of the dislocation density in the epilayer. The reduction of dislocation density after thermal cycling is clearly observed.

Photoluminescence Surface State Spectroscopy for
In-Situ Semiconductor Surface and Processing Characterization

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In this paper, a new photoluminescence (PL) surface state spectroscopy technique is presented which allows, for the first time, in-situ, non-destructive and contactless evaluation of the surface state density (N_{ss}) distributions on fresh and processed semiconductor surfaces. Previously, the N_{ss} distribution can only be measured either by the scanning tunneling spectroscopy technique for ultraclean surfaces, or by the C-V technique for MIS structures where insulator deposition inevitably changes the surface properties.

The new method consists of a detailed measurement of the band-edge PL efficiency spectrum (defined as the PL intensity, I_{PL} , divided by excitation intensity, ϕ plotted vs. ϕ) and a subsequent rigorous computer analysis. The previous assumption of a constant surface recombination velocity, S , is shown to be totally incorrect, and that the reducing behavior of S with excitation intensity is shown to reflect delicately the detailed properties of surface states causing surface recombination. The basic principle for data analysis is the following. At high intensities, the PL efficiency approaches an intrinsic value determined by radiative and Auger recombination. At low intensities, it takes a much lower value depending on the energy depth of the surface Fermi level pinning. In the transition region between these two limits, photo-induced unpinning takes place where the behavior is very sensitive to N_{ss} distribution. It can be shown that the Fermi level pinning position can be determined from the efficiency difference between two limits, the shape of N_{ss} distribution, from the slope of the spectrum in the transition region, and the density, from the excitation intensity around which transition takes place, respectively.

A fully computer controlled PL efficiency measurement system was developed in which the PL efficiency is automatically measured on the sample surface placed in the PL chamber under vacuum or in inert gas ambients. The PL chamber is connected to MBE growth, photo-CVD insulator deposition, chemical treatment, metal deposition and XPS analysis chambers.

The measured distributions on the wet and dry etched surfaces of Si, GaAs, InP and InGaAs are generally U-shaped with characteristic charge neutral minima, being consistent with the DIGS (disorder-induced gap state) model. Sulfur treatments on GaAs were shown to introduce fixed surface charge rather than reducing N_{ss} . Appearance of discrete state was observed on thermally annealed GaAs surfaces. Remarkable PL efficiency enhancement and N_{ss} reduction are achieved by insertion of an ultrathin MBE Si layer on the passivated surfaces of InGaAs.

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Studies of GaAs Surfaces by Scanning Tunneling Induced Photon Emission

Scanning tunneling microscopy has been shown to be a powerful tool for the characterization of surface properties on an atomic scale.

Such evaluation facilities are particularly relevant for modern nanometric structuring. Relevant measurement techniques, particularly the possible derivatives of this microscopy, based on piezo-actuator-control, are to be briefly reviewed and new concepts to be presented. In particular a scanning tunneling microscope has been used in order to induce photon emission out of p- and n-doped GaAs surfaces. A photomultiplier with GaAs cathode was used to detect the emitted photons. The influence of contamination layers, surface defects, tunneling current and tunneling voltage on light emission has been studied in detail. A lateral resolution in the nanometer range was obtained.

We could show that the photon flux is much more sensitive to surface contamination than topographic studies. Besides this we examined a GaAs sample with several scratches in the surface that could be clearly seen in the photon map. In the topographic image the scratches have a width of about 30 nm whereas in the photon map the width seems to be 200 nm.

GATED PHOTOLUMINESCENCE AND RAMAN SPECTROSCOPY ANALYSIS OF InP INTERFACES

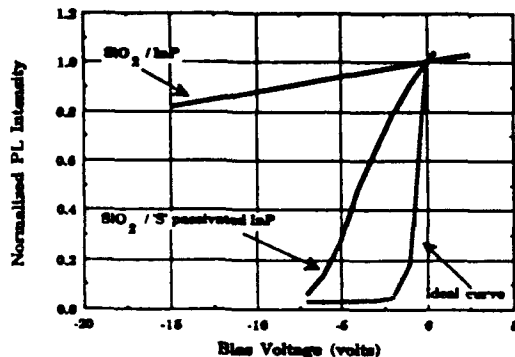
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Photoluminescence (PL) and Raman spectroscopy have long been recognized as powerful and non-invasive techniques for the characterization of materials properties. Due to the relatively short penetration depth of the excitation radiation these methods are particularly sensitive to near surface phenomena and have been used in many cases for the evaluation of surface related parameters, including surface potential, and surface recombination velocity.

As an extension of these methods we have investigated the use of gated PL and Raman spectroscopy as tools to evaluate the surface quality of semiconductors. In this approach the PL and/or Raman spectrum is measured through a transparent and conducting electrode, to which is applied a dc bias. We have found InP and InSb to both be particularly amenable to this technique, and we have used this approach to examine the effects of various physical and chemical treatments on the surface state density of these materials.

In this paper we will discuss the method, both its strengths and disadvantages, and will present data obtained on InP after various surface treatments including, in particular, the use of sulfur passivation, and thermal annealing.

The advantage of combining both Raman and PL evaluation, whether directly, or in a gated measurement, will also be discussed in light of the fact that the Raman response is directly sensitive to surface fields whereas PL probes both the field and the surface state density. With the availability of both spectra it should be possible to extract, less ambiguously, information on surface parameters.



The PL intensity, normalized to its value at zero bias, plotted as a function of gate bias for unpassivated InP, and sulfur passivated InP. Also shown is the theoretical curve calculated from Eq. (2) and the theory of Poon and Card

**Opto-electronic Modulation Spectroscopy(OEMS)
- A New Tool for Device Investigations**

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OEMS is an impedance spectroscopy which allows the variation of modulated device impedance to be seen in response to small periodic variations in the photon energy of incident light. Typically the impedance is measured at a few hundred kHz and the photon energy modulation is at a few hertz.

It will be shown how it can be used with sub band-gap illumination to directly measure the energy location of surface and bulk states and is able to distinguish between them. It overcomes the limitation which is inherent in normal C-V and G-V measurements. Data will be presented from observations made using metal-insulator-semiconductor structures but the technique is equally applicable to junctions and Schottky barrier structures.

If super band-gap illumination is used, necessitating illumination of the front surface, it is possible to observe the responses caused by states that overlap or resonate with the energy bands. An example will be given of its use in this mode to reveal what we believe to be the DX centre in GaAs. Generally this is only observable by conventional means if hydrostatic pressure is used to bring the state into the energy gap. OEMS allows its energy position to be measured directly.

The shape and phase of the spectral responses is in part determined by the energy variation of the optical cross-section of the state, allowing its form to be clearly seen. We will also demonstrate that if the potential variation within the depletion region being probed is known it is then possible to infer the separation of the responding states from the interface.

The technique is capable of use in a variety of modes including observations of the modulated response of channel currents in FETs. We will show data for GaAs IGFET structures that has provided information complementary to that observed in the corresponding MIS structure. We will point to other possible applications.

* on sabbatical at Ecole Centrale de Lyon

A Study on IR Light Intensities Scattered from Defects in an In Doped LEC GaAs Crystal as Functions of Wavelength and Intensity of Bias Light Superposed on the Defects

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ABSTRACT

The light scattering tomography is very useful to detect micro defects and to indicate two and / or three dimensional distribution of the defects. This method has been improved for its detection limit and some applications have been considered. In this paper, two beam method is introduced. The light scattering tomography with the superposition of monochromatized light as a bias is applied on determination of the energy levels due to defects inside the crystals. The intensity of scattered light changes as a function of the wavelength and intensity of the superposed monochromatized light. The peaks observed near 1290nm and 1050nm coincide with the photoquenching spectrum and also with the recovery energies of the EL2 obtained by PL method. Then, the energy levels of defects and their spacial distribution are determined by light scattering method and precipitates on the dislocations show EL2 levels which are vague to a few hundred μm .

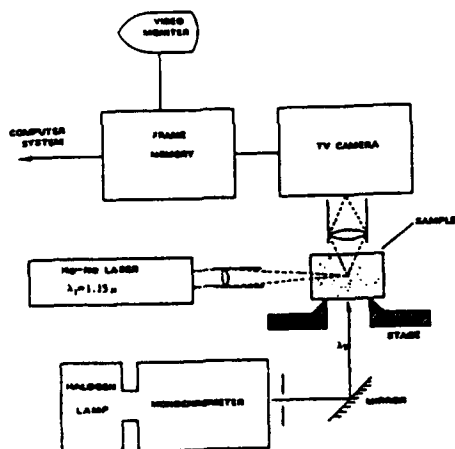


Fig. 1

Schematic drawing of the two beam light scattering tomograph system.

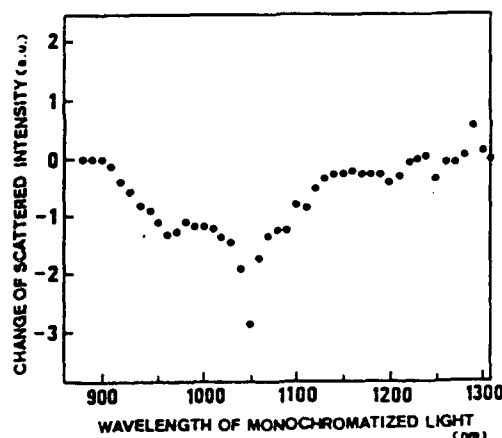


Fig. 2

The change of the scattered intensity as a function of the wavelength λ_2 of the monochromatized light superposed.

OPTICAL NDT FOR EVALUATION OF MICROPRECIPITATES IN SEMI- CONDUCTOR MATERIALS AND DEVICES

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Montpellier Cédex 5 - FRANCE

ABSTRACT

As semiconductor technologies evolves from micronic to submicronic scale the devices become more sensitive to built in defects which were not considered previously because of their very reduced size. More especially the metallurgy of the materials and the various fabrication steps give birth to small aggregates of foreign or excess atoms which size is nanometric and density in a range over 10^{10} cm^{-3} . Available observation techniques are not so many to non destructively reveal these flaws inside the materials.

Of course photon based techniques more consistently fit with the need of a non invasive non destructive inspection. Laser Scanning Tomography (LST) was the first solution to provide three dimensional information on scattering particles as small as 1 nm in bulk semi-conductors. Numerous investigations were performed in III-V compounds as well as in Silicon where this method, to date, is the only realistic way to study the generation of oxide related internal gettering centers. Recent results in the field are summarized.

Nevertheless LST images cannot be easily obtained from regions underlying the surface because of the excessive scattering occurring from any surface artefact (defects as well as structures). It follows that specific modifications have to be introduced in the technique even if the the basic argument of light scattering images is still preserved. T Ogawa recently showed that silica particles in SIMOX layers can be investigated using a Brewster illumination whereas Fillard and Montgomery have revealed grown-in particles in MOCVD GaAs layers. A review of these investigations is presented also with some conclusive experiment on devices: it was demonstrated that GaAs MESFETs structures can be inspected from the interior showing for instance process induced aggregates in Gate recess zone or showing the disordered internal interface of ohmic contacts.

These techniques are still in progress with a new method of particle sub-micron ranging called Nanolidar which is intended to evaluate the position of particles with a very high precision. This makes it possible to explore layered structures and to identify the exact location of the disturbing defects introduced by the epitaxial or annealing processes. The present state of the art is detailed.

Optical Characterization of Si Wafers for ULSI

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Non-destructive and non-contacting characterization is one of the most important and long-awaited technologies for ULSI (ultra-large scale integrated circuits) such as 64 Mbits and 1 Gbits memory devices. For this purpose, the most promising candidates will be optical methods including infrared (IR) ones.

(1) Micro-precipitates (MP) and micro-bulk defects (MBD) by IR light scattering tomography.

MP and MBD are very important for the intrinsic gettering action and perfectness of the denuded zones in Si wafers, which are closely related to behavior of oxygen atoms in and out of the wafers during their heat treatment. IR light scattering tomography (IR tomography) is very useful for detection and numerical evaluation of density of MP and MBD.

(2) OSFs and defects just under a wafer surface by visible light and Brewster angle illumination.

Refractive indices of semiconductors are usually more than 3 and then Brewster angle illumination is necessary to get good enough scattered light intensity from the defects by illumination because the p-component of the incident light will completely penetrate into the specimen while the s-one will specularly reflected at the surface. Here, even if the energy of photons is larger than the band gap of semiconductors, the photons will practically penetrate into the region of a few wavelength of the photons from the wafer surface and will be scattered by defects and precipitates there. The effective penetration depth of the photons will depend upon the photon density, scattering amplitude of the defects and also the detectability of the scattered photons in the measurement system. Therefore, the defects just under the surface will be detected by the light scattering from them, while the light will be scattered by plate-like defects as similar as the defects were mirrors.

(3) Bonded Si wafers and SIMOX

To realize good electrical isolation between electronic elements on Si wafers, bonded wafers and SIMOX have been proposed, where the bonded wafer was prepared by bonding thermally oxidized Si wafers at their oxide surfaces and then one of the wafers was polished into a few tens nm, and SIMOX was prepared by heavy dose implantation of oxygen ions into Si wafers and then by thermal annealing to remove radiation damages for recovery of crystalline perfection. The thickness and its homogeneity of the bonded wafers are measured by visible monochromatic light as a sort of equal thickness interference fringes. The thickness and crystalline perfection of SIMOX is also measured and characterized by the ultra-thin interference fringes discovered by the present authors.

**The Effects of Probe Power Density on the Spatially Resolved Room
Temperature Photoluminescence of Optoelectronic Epitaxial Structures**

by

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Spatially resolved room temperature photoluminescence has been reliably used to predict the performance parameters of optoelectronic devices such as PIN diodes [1]. However, attempts to compare correlations developed at different institutions have led to difficulties in the interpretation of the data and the nature of the correlations produced. This paper will examine the effect of varying the pump power (by more than two orders of magnitude) on the photoluminescence intensity of a simple three layer epitaxial InGaAs on InP structure.

Particular emphasis will be placed on the changing PL contrast mechanisms seen in these measurements as well as the change in the statistical behavior of the average value and standard deviation of the measurement. A phenomenological explanation of the results will be presented and a brief discussion as to the implication of these measurements for device correlation will be presented.

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POSTER PRESENTATIONS

Be⁺ ion implantation in Ga(Al)Sb layers. Radiation damage

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I - INTRODUCTION

Ga(Al)Sb compounds are good candidates to realize high performant, low-noise avalanche photodetectors (APD) in relation with the high ratio of the ionization coefficients of holes and electrons k_p/k_n occurring for a low aluminium content (about 5 %).

Efficient devices need a lot of optimized technological processes like metal deposition, junction realization, photolithography, chemical etching. In order to realize the junction we carried out a study on the implantation of Ga(Al)Sb layers ; procedure is given so as the characterization of the implanted layer after annealing. The photodiode is then performed from a classical mesa technology.

II - EXPERIMENTAL PROCEDURE

A. The Ga(Al)Sb layers : A series of Te low-doped $\text{Ga}_{0.06}\text{Al}_{0.04}\text{Sb}$ layers was grown on (100) oriented n⁺ type GaSb substrates by Liquid Phase Epitaxy (LPE) ; their doping level is around $1-2 \times 10^{16} \text{ cm}^{-3}$ and the Al composition leads to 1,55 μm photodetection.

B. Be- ion implantation : The optimized parameters of Be-ion implantation into Ga(Al)Sb (energies and fluences) have been determined from computer simulations using the TRIM code. The goal in the n-type layers was (i) to realize a 0,5 μm deep p⁺/n junction, (ii) to avoid a conduction-type inversion at the surface and (iii) to minimize the damage creation in the implanted layer. For this purpose a double implantation was performed. A first implantation at energy of 100 KeV and a dose ranging from 10^{13} to $4 \times 10^{13} \text{ ions cm}^{-2}$ was followed by a second implantation at energy of 50 KeV with the same dose.

Experimental Be distributions obtained by Secondary-Ion Mass Spectrometry (SIMS) measurements are in good agreement with the simulated computed one.

C. Damage Creation :

•Simulation

Using TRIM code it has been possible to simulate the damage production in GaSb crystals bombarded with Be-ions. Energy loss computation leads to the conclusion that 90 % of the energy is transferred to the electronic system of the target when only 10 % is dissipated by nuclear elastic collision.

•Channeling study

This study was carried out on as-grown layer such as on double-implanted samples before and after annealing in various conditions. From Rutherford Back Scattering (RBS) spectra we can conclude that the as-grown layers are of good quality. This effect is supported by the value of χ_{min} determined for the Sb sublattice of about 4 %. The damage produced by the Be implantation is directly responsible for an increase in the minimum yield χ_{min} which reaches the value of about 10 %. This low increase is in agreement with the damage simulation results demonstrating the low defect production rate of light mass implanted ions such as Be. After appropriated heat treatments (15 min, H₂, 450° C) this damage value is decreased close to the initial one.

•Electrical measurements

Hall effect measurements were carried out by delineating Van der Pauw samples using photolithography technology on good quality p⁺ (implanted layer)/n (epitaxial layer) junctions. The results proved that a total activity of Be implanted ions are observed.

•Mesa devices

Good quality photodiodes were realized starting from these implanted junctions allowing us to measure the k_p and k_n values; for $x_{\text{Al}} = 5 \%$ the ratio was found to reach $k_p/k_n > 10$.

CONCLUSION

Be⁺ ions implantations at energies of 100 KeV and 50 KeV and doses about $210^{13} \text{ ions/cm}^2$ lead to a very low damage level in the Ga(Al)Sb layers allowing the Be⁺ ions to be good candidates for doping III-V compounds.

INVESTIGATION OF ELECTRICALLY ACTIVE DEFECTS IN PLASMA ETCHED GaAs

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Plasma etching of epitaxial n-type GaAs in the temperature range of 77-573 K was found to lead to creation of electrically active defects detected by high sensitive DLTS technique. The aim of the present study was consisted in the determination of the origin of plasma induced defects, investigation of their properties and the mechanism leading to defects formation. Based on the comparison of the properties of plasma induced defects with those generated during high energy electron irradiation as well as on orientation effect observed in the case of differently orientated GaAs subjected to ion beam etching, the former were identified with Ga-related intrinsic point defects.

Their essential feature is rather high mobility so as they can penetrate into the crystal bulk down to some micrometers during room temperature storage.

Besides they were found to be very efficient recombination centers controlling the minority charge carrier lifetime in the layers of some micrometers in thickness.

To understand the contribution of various constituents of plasma etching such as electron and ion bombardment, chemical reactions on the crystal surface, UV and X-ray irradiation, we used different regimes of plasma etching (RIE, PE, IBE). Ion bombardment of the surface was found to be the main reason for defect formation. At the same time it was observed that defects created could change their charge state under simultaneous or subsequent illumination. The role of atomic hydrogen participating in the processes of both defect formation and modification of defect electrical activity was investigated.

MAPPING AND PROFILING OF DIFFUSION LENGTH AND
DEPLETION REGION WIDTH IN GaAs SCHOTTKY DIODES

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The diffusion length of minority carriers L is very important parameter which determines the characteristics of various semiconductor devices. So the development of methods for local measurements of this parameter becomes more essential. Up to now a lot of techniques is proposed to obtain this parameter from electron beam induced current (EBIC) measurements. As a rule it is necessary to measure the dependence of EBIC on electron beam energy E_b or on the distance to collected junction. The former technique has higher lateral resolution and it is more suitable for diagnostics of micron and submicron structures. But there is no way to determine true value of L if it depends on depth in submicron range that is the case for many compound semiconductor structures (f.e. MODFET). Other difficulties are associated with nonhomogeneity of depletion region width W which also influences on collected current value. Besides for mapping it is necessary to measure dependence I_c on E_b in each point because only in this case it is possible to obtain L and W separately. In this paper we propose a new way to overcome these problems by using EBIC and dI_c/dW signals. It is shown that expression for L can be written in analytical form using these two values even in the case of unknown diffusion length profile. A simple technique which allows to obtain two-dimensional L and W maps and local profiles of these parameters is developed. Examples of measurements of two-dimensional distribution of L and W on GaAs single crystals are presented. There are many important cases when L depends on depth. for example it takes place after some technology treatments such as external or internal gettering, dry etching etc. The examples of L profile reconstruction in GaAs and Si<Au> after reactive ion etching are presented. The comparison of profile reconstructed from EBIC measurements shows a good correlation with that measured by DLTS.

**INFLUENCE OF THE SUBSTRATE ON THE DIFFUSION LENGTH
AND THE INTERFACE RECOMBINATION VELOCITY OF GaAs
HOMOSTRUCTURES
DETECTED BY SEM/EBIC EXPERIEMENTS**

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The high quality of optoelectronic materials, required for the development of submicron devices, can be assessed by means of various techniques. The use of an electron beam in a scanning electron microscope (SEM) to induce a minority carrier current (EBIC), allows the characterisation of a semiconducting specimen in a volume of about a few μm^3 . Up to now, most of the EBIC studies have been devoted to the determination of the minority carrier diffusion length L and of the doping level in bulk specimens.

In this paper, we present an EBIC characterisation of homostructures which resemble field emission transistors. The dependence of the EBIC collection efficiency on the electron beam voltage is investigated for the particular case of a GaAs homostructure where the uppermost layer, silicon doped ($n = 4.10^{17} \text{ cm}^{-3}$) is grown on a p type ($p \approx 10^{15} \text{ cm}^{-3}$) layer, the substrate being semi-insulating. The minority carrier diffusion length L and the doping level N_D of the uppermost layer, as well as the first interface recombination velocity V_1 can be determined by this technique. The experiments, performed on two homostructures, grown by molecular beam epitaxy at 580°C in the same conditions, on SI substrates supplied by different manufacturers, indicate the influence of the substrate on the values of L , N_D and V_1 .

DEFECTS AND UNIFORMITIES IN MOCVD HgCdTe AND GaInAsSb GROWN ON GaAs SUBSTRATES

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The MOCVD HgCdTe and/or GaInAsSb epilayers grown on GaAs substrates have received considerable attention in long wavelength optical telecommunication and infrared technique. In this paper we present the growth of intermediate (and strained) layers between GaAs substrates and HgCdTe and GaInAsSb epilayers, studies of the defects in their interfaces and determination of uniformities in these epilayers.

The intermediate layers were deposited onto single crystal (100) GaAs substrates at growth conditions describable elsewhere in a horizontal MOCVD system under atmospheric pressure. After having obtained specular intermediate layers, the HgCdTe and/or GaInAsSb epilayers were then sequentially in situ prepared on their tops.

The defects and uniformities in intermediate layers, epitaxial layers and at their interfaces were examined. TEM and HREM show the presence of defects near or at the interfaces between intermediate and epilayers, but it is dramatically reduced, if the intermediate layer thickness is controlled to a critical value. In 77K PL spectra a broad peak at about 1.5eV due to so-called defect luminescence in HgCdTe epilayers and a acceptor level of about 30 meV above the valence band in GaInAsSb ones were observed. The typical double crystal rocking curves have FWHM of about 200 and 300 arcsec for HgCdTe and GaInAsSb epilayers respectively, which indicates their rather good crystalline quality. The results obtained from Roman scattering spectra of HgCdTe intermediate layers were coincide with those from double crystal diffraction, while that of GaInAsSb ones show the LO peaks at 237cm^{-1} , weak TO peaks at 221cm^{-1} and low background scattering intensity. The composition uniformities in HgCdTe and GaInAsSb epilayers determined by electron microprobe analysis illustrate very uniform Hg and In concentration in HgCdTe and GaInAsSb epilayers respectively, which agrees with the results obtained by PL and Roman scattering measurements.

The correlation of defects and uniformities in HgCdTe and GaInAsSb materials with electrical properties of epilayers and photoelectric detectivities of devices was discussed.

TERNARY AND QUATERNARY III-V SEMICONDUCTORS GROWN BY HVPE

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A comprehensive work concerning ternary (InGaAs) and quaternary (InGaAsP) III-V compounds grown by a quasi-equilibrium technique (HVPE) is in progress in our laboratories (1,2), in order to investigate factors affecting the properties of the epitaxial layers.

Several techniques are used for characterization (3), in particular secondary ion mass spectroscopy (SIMS) and Rutherford backscattering (RBS) in order to assess film thickness and interface profiles, while the "mismatch" with respect to the substrates is measured by multiple crystal diffraction.

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GENERALIZED ANALYSIS ON THE PHOTOVOLTAGE DECAY CHARACTERISTIC OF SOLAR CELLS.

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ABSTRACT : In order to determine the excess minority carrier lifetime and back surface recombination velocity in the base of solar cells, a new mathematical analysis of light pulse spectral effect on the transient photovoltage decay (PVD) is presented.

The same analysis has been performed for the composite light pulse effects on the transient photovoltage PVD through the approximate generation rate of excess minority carriers [1].

Since a constant bias light is superimposed on the light pulse excitation, the initial steady state voltage and the asymptotic voltage are taken into account in the mathematical expression of the transient PVD.

The decay behaviour of the open circuit photovoltage is influenced by either the monochromatic light pulse wavelength or the composite light pulse, and also by the initial and asymptotic steady states.

The intercept technique [2] of the fundamental mode with time zero axis and decay measurement is applied to interpret the available PVD curves [3].

The results obtained enable us to understand the discrepancies among excess minority carrier lifetime from the models reported earlier.

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INFLUENCE OF THE BASE p-TYPE DOPANT (Be,Zn,C) ON Mg DISTRIBUTIONS IN Mg-IMPLANTED HBT DEVICES

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GaAlAs/GaAs Heterojunction Bipolar Transistors (HBTs) are of great interest as high-frequency devices. In order to increase the frequency performances, we are developing an implanted self-aligned technology [1] in which the base layer is contacted from the surface. This technology permits to keep a planar emitter-base junction and also to reduce the current gain size effect.

In this paper, we will present a comparison of the interactions between the implanted Mg for which the implantation process has already been optimized [2], and the different p-type base dopants which can be used in HBT structures. Indeed, the base p-type dopant can be either Be, Zn or C. Different analyses have been carried out to investigate the influence of the p-type dopant on the Mg distribution. Secondary Ion Mass Spectroscopy (SIMS) analysis was performed before and after annealing to determine the Mg and the base dopant atomic profiles. Be and Zn were found to diffuse due to the Mg implantation, while this effect was not detected with the C dopant. The Mg atomic profile after annealing was found to be strongly affected by the presence of Be or Zn, while the influence of C was much less important. The electrical profiles, obtained after annealing by C-V electrochemical profiler measurements, also show the influence of the base dopant on the electrical results.

Different behaviours have been observed according to the different base p-type dopants; these behaviours will be detailed and explained. The absence of interactions between C and Mg will be pointed out, showing that C p-type dopant is very promising for the fabrication of small dimension devices.

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A QUASI PLANAR GaAlAs/GaAs HBT WITH ALL OHMIC CONTACT IN TUNGSTEN MADE BY SELECTIVE AREA CHEMICAL BEAM EPITAXY

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High speed circuits with GaAlAs/GaAs Heterojunction Bipolar Transistor have been realized, but either the self-aligned technology or the classical double mesa technology are facing several difficulties: the transistor is not planar which can be a limitation for integration, and the gold base ohmic contacts are not stable at temperature over 450 °C.

To overcome these difficulties and to obtain a quasi planar self-aligned HBT with all the ohmic contact in tungsten, a new technology based on Selective Area Epitaxy (SAE) of GaAs and related materials by Chemical Beam Epitaxy (CBE) is proposed.

Three Selective Area Epitaxy steps are used. The first one, after a mesa etching from the surface to reach the semi insulating substrate, corresponds to a selective regrowth of undoped GaAs in order to isolate the HBT. The second regrowth, after a hole etching to reach the subcollector, is made with N+ doped GaAs and GaIn_{0.65}As in order to realize the collector ohmic contact in tungsten. The third one, after a hole etching to reach the base layer, is made with high P+ doped GaAs (10^{20} cm^{-3}) in order to realize the base ohmic contact in tungsten. At the end of the process all the ohmic contacts are in tungsten, and the final HBT is quasi planar.

All the mesa and hole etching in GaAs to reach the different HBT's layers are realized by RIE (SiCl₄ gas). SiO₂ or Si₃N₄ spacers on the sidewalls holes are also used to isolate the active HBT's layers from the selective epitaxy, in particular in the case of the N+ and P+ SAE which contact the collector and base layer respectively.

In this paper we will report the SAE growth conditions, the characterisation of regrown layers, the electrical results on test pattern to contact the collector, and finally the first results on big transistor to validate this new approach.

Arsine, triethylgallium (TEGa) and trimethylindium (TMIn) are used for the CBE growth of GaAs and GaInAs. P type and N type dopant sources are respectively trimethylgallium (TMGa) and tetraethyltin.

The control of selective growth (no deposition on the Si₃N₄ masks) of GaAs and GaIn_{0.65}As is obtained above a critical temperature respectively of 650 °C and 550 °C.

In the case of the N+ selective regrowth for contacting the subcollector, an optimization of the growth conditions have been performed in order to avoid, at the regrowth interface, a compensation effect related to carbon surface contamination and to the delay time of the incorporation of Sn dopant. The surface preparation and the initial growth conditions will be describe to achieve the requirement of a low resistivity between the subcollector layer and the selective N+ epitaxy. The end of the epitaxy is made with GaInAs to allow a tungsten ohmic contact. After a description of the test pattern, the electrical results will be discussed, a contact resistivity of $10^{-6} \text{ Ohms cm}^2$ have been obtained by the Transmission Line Model.

The morphology of the SAE is perfect, except some crystallographic plans which are revealed near the sidewalls. This leads to the formation at the surface of the final processed HBT of a smooth step with a thickness equal to about 10 % of the regrowth thickness. So the final HBT will be quasi planar.

Nitridation of thermal SiO₂ thin films studied by Auger Electron Spectroscopy

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Nitridation of thin SiO₂ films (10-15nm thick) thermally grown on Si(100) modifies the SiO₂ structure in such a way to make it impervious to contaminant diffusion and to preserve the SiO₂/Si interface electrical quality.

Since the nitrogen incorporation in SiO₂ is essentially surface limited, Auger Electron Spectroscopy (AES) is a suitable technique for studying the corresponding nitridation kinetics. Moreover, due to its high lateral resolution AES, is particularly convenient to follow the homogeneity character of the SiO₂ superficial nitridation and the physicochemical changes induced.

We show that the characterization without destruction of the oxynitride thin film formed upon reaction is possible using limited primary electron current densities (electron doses < 10²⁰e-.cm⁻²), rastered electron beams and by probing various sample areas. It is well known that silicon dioxide, silicon oxynitride and silicon nitride thin films are reduced under electron bombardment. Using our experimental conditions, no destruction was observed during the analyses as shown by the absence of the Si(LVV) Auger transition at 88-90eV generally associated with thin film reduction.

Finally, the energy position of Auger peaks for Si, N and O give information versus the time of reaction about the chemical environment of the involved species, whereas the nitridation content can be deduced from the Auger peak intensities.

STUDY OF DEFECTS IN INDIUM PHOSPHIDE BY DSL AND LST

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ABSTRACT

The study of defects in indium phosphide has been carried out using diluted "Sirtl - like" mixtures used in the dark (DS) or under illumination (DSL), and laser scattering tomography (LST). The revealing of defects in this material is usually realised by crystallographic etchants such as Huber etchant or Chu etchant which produce etch pits on dislocations in the semiconductor. Unfortunately, these latter techniques do not give rise to the possibility of studying the chemical inhomogeneities of the material.

DSL photoetching has been developed by Weyher and co-workers. The system is well calibrated for revealing defects in gallium arsenide, where it is very sensitive for various types of crystallographic imperfections and chemical inhomogeneities.

We have studied the method for use with indium phosphide and it is shown that a wide range of compositions produce features related to defects in different types of the material. These etch figures consist of hillocks or depressions, depending on the electrical property of the semiconductor. Comparisons with photoluminescence and Huber etch shows that they correspond to different types of defects: (i) dislocation (decorated or not); (ii) individual matrix precipitates; (iii) growth striations.

The results are compared with those from LST and applied to the study of various substrates and epitaxial layers.

**PHYSICOCHEMICAL CHARACTERIZATION BY MEANS OF INFRARED
ABSORPTION SPECTROSCOPY OF Si_3N_4 THIN FILMS OBTAINED FROM
C.V.D. ASSISTED BY IN-SITU ELECTRICAL DISCHARGE**

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ABSTRACT :

In order to obtain insulating thin films, an original process has been developed which enables the fabrication of insulating (Si_3N_4 , SiO_2 ,...) thin films, by means of an *in-situ* activation of the reactions at low temperature ($T < 400^\circ\text{C}$) and under low pressure ($P = 1$ to 2 torr). The activation is performed by a DC electrical discharge. The substrate is not used as an electrode. It is placed parallel to the electric field. During the deposition process, several activation mechanisms can interfere : UV activation (UV photons generated by the reaction gases), photo-sensibilization, direct activation by impacts (as it is observed during thermal activation), and various thin films have been obtained.

The compositions of layers having various widths have been analyzed using Infrared absorption spectroscopy. With temperatures higher than 200°C , Infrared investigations showed the presence of great amounts of both the Si_3N_4 nitride and hydrogenated species (NH , NH_2 , SiH), and no Si-O bonds. For lower temperatures, all the IR lines assigned to bonds with nitrogen decreased and Si-O lines increased in intensity. This can be interpreted in terms of a degeneracy of Si_3N_4 towards oxinitrides. Typical results obtained from Infrared spectroscopy are presented. They show how Infrared spectroscopy can be used as an interactive analysis technique in the manufacturing of insulating thin films. The results obtained from Infrared analyses are compared to those obtained from other physicochemical analysis techniques.

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APPLICATION OF DEEP LEVEL TRANSIENT SPECTROSCOPY FOR MONITORING
POINT DEFECTS IN III-V SEMICONDUCTORS

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The main electrical and optical properties of III-V semiconductors strongly depend on their defect structure which is formed by various point defects generated during material growth and device manufacturing. In the vapour phase epitaxial layers of $\text{GaAs}_{1-x}\text{P}_x$ and GaP with low resistivity, which are used as starting materials for electroluminescent devices, deep defect centres are studied by transient capacitance spectroscopy. A number of donor-related deep-level defects have been found. Apart from doping level, the defect structure of these materials is affected by the III-V ratio, dislocation density and growth temperature. The reactions leading to formation of the grown-in deep-level defects are discussed. The effect of these defects on the radiative recombination efficiency is presented. In the high-resistivity bulk crystals of GaAs:Cr, undoped GaAs and InP:Fe, which are starting materials for monolithic microwave integrated circuits and high-speed digital circuits, deep defect centres are studied by photoinduced transient spectroscopy (PITS). The characteristics of thermal emission rate of charge carriers as a function of temperature and activation energies of deep centres have been determined. The effect of the Fermi level position on the PITS signal has been established and a tentative identification of the deep-level centres has been performed. The defect structure of semi-insulating GaAs crystals with various carrier mobility is compared.

Optical Thickness Mapping of Epitaxial Layers

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The thickness of epitaxial layers is an important parameter in optoelectronic devices. MOVPE processes have to be extensively optimized in order to achieve homogenous and reproducible layers. The existing methods are either destructive (step profiling) or complicated and limited in their applications (ellipsometry).

We present a two-wavelength transmission method which allows to measure epi-layer thicknesses even of buried layers and heterostructures. The method is non-destructive and reaches a vertical resolution of better than 10 nm. Layer thickness can be mapped with high lateral resolution obtaining a profile image of the epi-layer.

The method is explained along with some examples. An apparatus is shown that combines the two-wavelength method with scanning photoluminescence for a multifunctional characterisation of epitaxial layers.

Other applications of the two-wavelength transmission method in the field of compound semiconductor technology are presented.

Low Frequency Noise as a Characterization Tool in InP and GaAs-based Double Barrier Resonant Tunneling Diodes

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This paper describes the application of low frequency noise measurements to characterize trapping parameters in InP and GaAs-based double barrier (DB) resonant tunneling diodes (RTDs) that have high-quality d.c. current-voltage characteristics. The derived noise of the tunnel diode can be modelled as a combination of a $1/f$ and *generation-recombination* (GR) components, in which the GR noise displays characteristic shoulders in the noise spectra due to its Lorentzian nature. Deconvolution of the diode noise spectra into discrete Lorentzian components using a non-linear least squares fitting algorithm, such as the Levenburg-Marquardt algorithm, allows for the determination of the corner frequencies (f_c) of these spectral components. Using generation-recombination theory, we can derive the relationship

$$\ln(T^2/f_c) = (E_A/k) \cdot (1/T) - \ln(B \cdot \sigma)$$

which relate the corner frequencies of the Lorentzians at several temperatures to the activation energy E_A and the capture-cross section σ . Therefore, graphing $\ln(T^2/f_c)$ versus $1/T$, E_A can be calculated from the slope, and σ from the intercept on the $\ln(T^2/f_c)$ axis. The constant k is Boltzmann constant, and B is related to the materials' properties of the RTD. In this paper, the measurement technique, relevant details of the noise spectra of the RTDs (in which the noise contributions from the biasing network is subtracted), experimental results and their interpretation for both GaAs and InP-based RTDs will be presented and discussed. For example, in the GaAs-based RTD, two traps with E_A 's of 135 and 200 meV and σ 's of $4.03 \times 10^{-16} \text{ cm}^2$ and $1.14 \times 10^{-17} \text{ cm}^2$ respectively were determined from noise measurements between 300K and 77K. In addition, high temperature results (300K to 400K) from InP-based RTDs, as well as an interpretation and model of the $1/f$ noise component in the noise spectra will be presented.

Electrical conduction in two-phase PbTe-Sb₂Te₃ alloys

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Electrical transport in multiphase alloys, due to their unusual electrical properties, has received the attention of several investigators recently. In the present communication electrical conduction in two-phase PbTe-Sb₂Te₃ alloys has been reported.

PbTe is a semiconductor with an energy gap of about 0.29 eV at 300 K whose conductivity sign and magnitude can be varied from 'n' to 'p' by controlling the proportion of lead and tellurium with respect to the stoichiometric ratio. Excess lead results in n-type conduction whereas excess Te imparts p-type conduction. Sb₂Te₃ is found to exist only as a p-type material of relatively high conductivity. The maximum solubilities of Sb₂Te₃ and PbTe in PbTe and Sb₂Te₃, respectively has been found to be less than 5%.

The test samples of various compositions have been prepared by pyrosynthesis of constituent elements under a vacuum of $>10^{-5}$ mm Hg in sealed silica capsules. XRD analysis reveals that all these samples are of two-phase mixtures. Qualitative measurements of thermoelectric power at room temperature (300 K) indicate that above 40 pct Sb₂Te₃ alloys are p-type while below this range alloys are n-type. The electrical conductivity of the sintered pellets of these alloys has been measured by Van der Pauw method. On alloying electrical conductivity of PbTe increases upto 20 pct Sb₂Te₃ and decreases thereafter upto 40 pct Sb₂Te₃. Beyond this composition conductivity further increases and attains a maximum value at about 80 pct Sb₂Te₃ and then decreases. From these observations it may be inferred that when an electron donor phase is added to a p-type semiconductor or a hole acceptor phase is added to a n-type semiconductor, there is initially a decrease in the potential barriers at grain boundaries causing an increase in the electrical conductivity. Further increase in the concentration of either phase results in conduction arising due to net effect of electron and hole concentrations available for conduction in the samples.

EBIC Microtomography of Microcracks in Silicon Plates.

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The Electron-Beam-Induced-Current (EBIC) mode in Scanning Electron Microscope (SEM) is widely used for study the internal structure of semiconductor samples. But the interpretation of images, obtained using this method usually causes great difficulties. The purpose of it is the diffusion character of the EBIC signal generation, which leads to the volume averaging of the information about sub-surface structure of a sample.

In previous works ^{1,2} it was described the method of EBIC tomography, i.e. layer-by-layer reconstruction of weak inhomogeneities in semiconductor samples based on complete computer processing of the number of EBIC images, obtained under different accelerating voltages in SEM. This method gives the opportunity to visualize plane sections of inhomogeneities under the sample surface. Since the most of dislocations, stacking faults, microcracks, etc. can be considered as weak inhomogeneities, it was predict that this method could be used to study the internal structure of semiconductor samples in three-dimensional, high-resolution mode.

In present work we describe the application of this technique for investigation of depth structure of microcracks, appearing in Si plates during mechanical polishing. Study of such cracks is very important, because they cause significant influence on outcoming characteristics of microelectronics devices. We used mechanically polished sample silicon plate lead by phosphor. In order to create p-n junction boron ions have been implanted to it's surface and then pulse heating was applied up to maximum temperature of 1180° C. The structure of these cracks is *a-priori* well known from previous investigations and described in literature.

On our computerized complex SEM JSM-35CF - IBM PC/AT we have acquired 13 EBIC images of one of these cracks under accelerating voltages from 8 kV to 38 kV. Then using our computer program we have got 13 plane sections of this crack structure, laying on depths from approximately 1.5 microns to 15 microns. All these sections do correlate well with *a-priori* known data.

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² Likharev S.K., Rau E.I., Trifonenkov V.P., Yagola A.G. *Induced-current microtomography of semiconductor structures.* - Soviet Physics. Doklady, 1989, 34 (8), 682-684.

SPL characterization of iron doped GSMBE indium phosphide layers

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Iron doped indium phosphide layers were recently obtained by gas source MBE growth, with resistivities as high as $1.5 \cdot 10^9 \Omega\text{cm}$, for an iron concentration of some $10^{17} \text{ ions cm}^{-3}$ [1]. We used the same technique and we also obtained iron doped high resistivity layers. The iron source was of high purity ; the iron concentration in the epitaxial layer ranged from $1 \cdot 10^{16}$ to $2 \cdot 10^{18} \text{ ions cm}^{-3}$. Various structures n/iron doped/n or n^+ /iron doped/ n^+ were implemented on a n^+ sulfur doped substrate as well as InP iron doped structures on SI substrate.

The scanning photoluminescence technique (SPL) at room temperature was used to characterize the samples. The measurements were interpreted in relative intensity (for integrated signals) and some were also spectrally resolved. Defects are revealed by SPL, with a density of some 10^4 cm^{-2} and a size of about $100 \mu\text{m}^2$. Under the same growth conditions, this density seems to increase with the iron concentration which was measured by SIMS. The SIMS profiles have an irregular shape for iron concentration larger than the iron solubility limit. Furthermore, iron was found to accumulate at the surface, as already observed for beryllium at high concentration, by Panish et al. [2].

In addition, the number of defects found on a sample, depends also on the growth conditions (III/V ratio, substrate temperature), as well as on the initial cleaning of the surface, or on the substrate type. Finally, growth temperature effects will be discussed.

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II^d Conf. CBE - Oxford - Sept. 91

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Photoluminescence characterization of oxidized Schottky diodes obtained by multipolar plasma oxidation of InP *

by

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InP is an attractive III-V compound semiconductor for high speed metal-semiconductor field effect transistors (MESFETs) and optical devices. The low value of the Schottky barrier height ϕ_B on n-type InP prevents its use in electronic applications. Thus many attempts have been made in order to increase ϕ_B by forming a thin oxide layer at the metal-InP interface.

In this work, band edge photoluminescence intensity measurements are used to study the modification induced by a multipolar plasma oxidation process and comparisons are made with results obtained from electrical analysis (current-voltage, capacitance(1MHz)-voltage). n-type (100)InP substrates having a free-carrier concentration of 10^{16}cm^{-3} were used. They were oxidized using multipolar plasma technology, and for comparison, Au-InP Schottky diodes were also fabricated.

To remove the native oxide the samples were first chemically etched in HCl (3N) for 2mn. A further step consists of an in-situ exposure to atomic hydrogen for 10s. Then oxidation in a multipolar oxygen plasma is performed during 15mn, with a plasma power of 100W and an oxygen pressure of 4×10^{-4} mbar. The oxide thickness deduced from ellipsometry is about 13nm. The samples are provided with semi-transparent gold electrodes.

The variation of the photoluminescence intensity I_p versus bias voltage V_g is stronger for the MS diodes than for the oxidized structures. The modification of I_p are related to the change in surface Fermi level position, and to the variation of the surface recombination velocity S , which is related to the interface density of states. It has been shown [1] that S remains low ($\leq 10^4\text{cm/s}$) and thus the width of the surface-space-charge region W , is the main parameter governing I_p changes.

Within the dead layer model, the experimental results for the Schottky diode are well reproduced by the theoretical formula $I_p(V_g) = I_{fb} \exp(-W(V_g)/d_{eff})$; I_{fb} is the flat band intensity and d_{eff} the effective penetration depth of the excitation beam. A modulation technique allows us the determination of the differential signal dI_p/dV_g versus V_g . The maximum signal corresponds to flat band bias condition, here 0.29V, which gives us $\phi_B = 0.4\text{eV}$ for the Schottky barrier height.

The $I_p(V_g)$ curve for oxidized structures exhibit a clockwise hysteresis which correlates well with those of C-V_g curves. The flat band voltage is about 0.4 and 0.5V for the positive and negative bias sweep rate respectively. In depletion, the decrease of I_p is much lower as compared to the MS diode. These results suggest at least a partial pinning of the Fermi level related with a higher interface state density.

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Investigations of Ohmic Contact Systems with Diffusion Barriers on n-GaAs

Continuing our work presented at the Wocsdice '91 /1/ we discuss further results concerning the electrical and microstructural properties of ohmic contact systems of the type "gold top layer/ amorphous WSi_3N_4 , or polycrystalline LaB_6 diffusion barrier layer/ internal ohmic Au/Ni/Ge layer" on epitaxial n-GaAs (and n-GaAs/ AlGaAs) in dependence on the metal layer and heat treatment parameters. The preparation procedures (cleaning, patterning, layer deposition, different annealing modes) and the diagnostics (mapping of the TLM-determined contact resistance R_c and concentration depth profiles of the relevant species by the SNMS method) are sketched. Lower limits of the layer thicknesses d of the internal ohmic layers for R_c optimization are determined. From R_c vs. d plots it can be followed that values of ≈ 40 and ≈ 25 nm for the total Au/Ni/Ge and partial Au thickness, respectively, are necessary to obtain the practically important $0,1 \Omega\text{mm}$ ($\leq 10^{-6} \Omega\text{cm}^2$) range. The results are discussed in a secondary phase model. - With respect to hetero-epitaxial systems R_c comparisons are made between the Au/ WSi_3N_4 /Au/Ni/Ge system (shallow alloying) and the conventional Au/Ni/AuGe or Au/Ni/Ge contacts (deep alloying).

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Photoluminescence characterization of GaInAs/AlInAs HEMT structures

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In this study, we describe the correlations between the photoluminescence (PL) spectra and electrical properties of high electron mobility transistors in the GaInAs/AlInAs system grown either with lattice matched ($x_{\text{In}}=0.53$) or strained ($x_{\text{In}}=0.6$) channel.

Strong radiative recombination of the two dimensional electron gas (2DEG) with photogenerated holes has been observed. The recombination is not k conserving since the holes are localized at the heterointerface opposite to the 2DEG region.

The excitation intensity-dependent and temperature PL experiments clearly show the evidence of a Fermi edge singularity in the PL spectra. Emission peaks associated with both the $n=1$ and $n=2$ electron subbands are observed depending on the electron sheet density in the well. Because of the Fermi edge enhancement mechanism, the position of the Fermi level can be measured optically relatively to the top of the $n=2$ and $n=1$ subbands by the linewidths of the PL spectra. The electron sheet densities so deduced are in good agreement with those measured by transport experiments.

Our results confirm the potential of photoluminescence for a contactless and rapid determination of the sheet carrier density in HEMTs. They can have applications in non destructive testing by photoluminescence of the uniformity of sheet carrier density on large area wafers.

Burst Noise in Reverse and Forward Current in the Lattice-Mismatched

InP/In_xGa_{1-x}As/InP Photodetector Arrays

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Technologies based on the lattice-mismatched III-V semiconductor materials give rise to some problems related to high concentration of material inhomogeneities and technologically-induced defects. This results in the lower fabrication yield and performances of photodetector arrays. One important parameter limiting the sensitivity of a photodiode is the low frequency stability of the reverse dark current. Routine check of these current fluctuations by a conventional CCD reading system at the working point of photodetector does not provide sufficient information about the character and physical origin of such a type of device failure. Therefore, a direct study of the current instabilities is necessary for the understanding of the phenomenon, allowing then an improvement of the technology.

In this work we have systematically studied low frequency fluctuations of the reverse as well as forward current in linear arrays of the photodetectors (spectral range up to 1.7 μ m) fabricated by different technologies on the lattice-mismatched InP/In_xGa_{1-x}As/InP (0.55<x<0.6) Low Pressure Metal Organic Chemical Vapour Deposition-grown materials. Selected photodiodes have been measured up to maximally 18V in reverse and up to maximally 3V in forward direction. We can distinguish three groups of reverse dark current waveforms at room temperature for biases less than 5 Volts. The first group consists of good diodes without significant current fluctuations. The second is characterized by flicker-like noise even for very low voltages. Finally, in the third one, we have observed the telegraph or also called burst noise (BN) which we have studied in details. The photodiodes from the last two groups have a higher dark current than those from the first one. Note, that even for the good diodes without BN at low voltages, this one can be sometimes observed at much higher voltages (>15V) in reverse direction and very often in forward direction.

We have observed discrete current fluctuations (BN) with amplitudes ranging from 1 pA to 300 nA and a time scale from 1 ms to 1 min, depending on the bias and varying from diode to diode. The relative magnitude of reverse current fluctuations varies between 1-40% while in the forward direction it is lower by one order. Usually, with increasing applied bias new current levels can appear, leading to generally multilevel signal. With further bias increase, the BN amplitude saturates and then BN transforms to chaotic flicker-like noise.

The random repetition frequency of BN is thermally activated. At a fixed bias, with decreasing temperature the pulse length increases and switching of reverse current gradually disappears below 200K. Higher voltages must be applied to reinitiate the BN. At 80 K, only switching of forward current is still observable in some photodiodes.

Illumination does not change the amplitude and switching rate of BN and their voltage dependence. This seems to be very important from the point of view of applications because, for example, at zero applied bias the BN is not present in the photocurrent.

As a physical origin of the observed phenomena we propose a modulation of a conductive channel by a change of the charge state of a defect located in the vicinity of it. We suppose that a surface channelling or a conductive path through the perturbed oxide could be the origin of such a channel. Both mechanisms can be related to the high density of dislocations and other type of macroscopic defects present in the material. As well, the influence of some technological steps as zinc diffusion, passivation layer deposition and ohmic contact annealing seems to play a role. These technologically-induced defects can be also connected with the dislocations.

ATOMIC SCALE SIMULATION OF LATTICE MISMATCHED HETEROSTRUCTURES : CASE OF CdTE/GaAS

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We have performed an atomic scale simulation of lattice mismatched heteroepitaxial growth of semiconductors with zincblende structure by associating the Monte Carlo technique with an energy model based on the Valence force Field (VFF) approximation. The aim is to investigate the formation of misfit dislocations, and the possible change of orientation of the growing layer, which may be (100) or (111), on a (100) oriented substrate.

The Monte Carlo technique is used to determine the set of events occurring on the surface, according to their activation energies. The VFF approximation is used to calculate the mismatch induced deformation of the deposited layer and the substrate; and to estimate the activation energies of different events. These are assumed to be stress dependent, the movements of the most stressed atoms being accelerated.

We have shown that at lattice mismatches higher than 10%, (111) oriented islands appear on a (100) oriented substrate, and that their proportion increases with increasing lattice mismatch. we have also evaluated the critical thickness for the creation of misfit dislocations. These are in good agreement with experimental results for high lattice mismatches (> 6%).

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TRANSPORT PROCESSES IN Au/n-InP AND Au/OXYDE/n-InP DEVICES TREATED IN OXYGEN MULTIPOLAR PLASMA.

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The high electron mobility and saturation drift velocity of InP may permit its use in the applications such as field effect transistors, laser diodes and photodetectors. However, the major limitation in metal/InP devices is the large value of the saturation current (10^{-1} A/cm²).

Several techniques of surface passivation, for example plasma oxidation, are now being studied in order to form an interfacial layer and thereby reduce the saturation current.

In this paper, the transport processes in Au/oxyde/InP (MIS) devices formed in oxygen multipolar plasma and metal-semiconductor (MS) Au/InP structures, are studied from J-V characteristics measured at temperatures varying from 200 to 400 K. For Schottky diodes with an interfacial layer, the thermoionic emission predicts the J-V relation for $V > 3kT/q$:

$$J = J_s \exp(qV/nkT)$$

where the saturation current density obtained from the experimental J-V curve is:

$$J_s = A^* T^2 \exp[(-q/kT) \cdot \Phi_{\text{Beff}}(T)] \cdot \exp(-a \cdot \delta \cdot X^{1/2}).$$

where $\exp(-a\delta X^{1/2})$ represents the tunnel probability through the oxyde layer, $\Phi_{\text{Beff}}(T)$ is the real barrier height; J_s can be also written in the form:

$$J_s = A^* T^2 \exp[(-q/kT) \cdot \Phi_{\text{Bapparent}}]$$

Now, from the slope m of the experimental curves $\Phi_{\text{Bapparent}}(T)$, one can determine the thickness δ of the interfacial layer:

$$\delta = (q/kaX^{1/2}) \cdot (m + \alpha) \quad ; \quad \frac{\partial \Phi_{\text{Beff}}}{\partial T} = -\alpha$$

The values of δ evaluated on MS devices are varying from 30 to 45 Å. For MIS structures, the thickness values deduced from our model are in good agreement with those obtained from ellipsometric measures.

The Richardson's constant of InP is also deduced from $\ln(J_s/T^2) = f(1000/T)$ curves; the constant takes values between 8 and 12 A.cm⁻².K⁻² in agreement with the calculated value 9.6 A.cm⁻².K⁻².

We conclude that the transport process in the MS devices and Schottky-MIS structures fabricated, is dominated by thermoionic emission with tunnelling through the oxyde layer at temperatures between 200 and 400 K.

**Determination of Refractive Indexes of InAlAs/InP in the
Wavelength Range from 300 to 1900 nm by Spectroscopic
Ellipsometry**

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The refractive index of MBE-grown $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ on InP has been measured by spectroscopic ellipsometry in the range from 250 to 1000 nm /1, 2, 3, 4, 5/. A preliminary fit for 1000 to 1500 nm was also given /5/, on a 0.5 μm thick MBE-grown $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ on InP. We found out, that a thin interface layer with a higher refractive index than that of InP and $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ exists, due to the interaction of Arsenic with InP in the preheat phase of the MBE growth.

To determine the refractive indexes and thicknesses of the $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ and the interface layers in the wavelength range from 300 to 1900 nm thin $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ (10 and 20 nm) MBE grown layers were investigated. We used two ellipsometers of Rudolph Research, the Spectro 2000 (type 437) in the wavelength range from 280 to 840 nm and the research ellipsometer (type 436) in the range from 410 to 1900 nm.

Assuming the interface layer to be InAs, we had good fits for both samples with a thickness of about 1 nm. A comparison of the refractive indexes of InP /5, 6/ and $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ in the range from 1000 to 1900 nm shows that the refractive index of $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ is higher. The difference between both decreases from 0.055 at 1000 nm to 0.030 at 1900 nm.

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Hall Mobility Profiling in HEMT structures

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ABSTRACT

We present results on Hall mobility profiles in HEMT structures as a function of depth of material removed. The profiles were obtained by a repetitive procedure whereby a thin layer of semiconductor material was etched away by a process of anodic oxidation followed by an oxide strip and the Hall mobility and carrier density measured at room temperature and 77K. The work was carried out on an existing commercial instrument, the HL5900+ Hall Profiler from Bio-Rad Microscience. Anodic oxidation was preferred to chemical etching because of the excellent control on the thickness removed, which also ensures reproducible results for a given HEMT structure.

The structures investigated were conventional pseudomorphic HEMTs on GaAs substrates. As expected, the sheet Hall mobility increased as the top layer was gradually removed, reaching a well-defined maximum value before the 2DEG was depleted. The maximum values ranged from 13,700 to 38,000 cm²/V/s at 77K and 3260 to 5880 cm²/V/s at room temperature. When the maximum in Hall mobility was reached, the sheet carrier densities at room temperature and 77K were found to be nearly identical, at about 1.2 to 1.8x10¹² cm⁻², which suggests that these values represent the properties of the 2DEG. We believe our results show that dual temperature Hall profiling is very useful in characterizing the growth process in HEMT structures as well as determining the optimal depth for the gate recess in practical devices.

THE LATTICE PARAMETER VARIATION OF InP HOMOEPITAXIAL LAYERS GROWN BY HVPE

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It is well known that the fundamental physical properties (mobility, band gap) and crystal perfection of III-V semiconductors are controlled to a large extent by small variations in the stoichiometric ratio between the respective constituents. This is thought as due to the generation of point defects (antisite defects, vacancy and interstitial) and extended defects such as precipitates, twins, stacking faults. In this respect several studies evidenced that GaAs under different conditions of thermal annealing (variations in As vapour pressure) exhibited large variations in its characteristics/1/. In the previous work /2/ we have studied the morphological aspects of surfaces and the nature of defects as a function of gas phase composition for homoepitaxial InP.

In this communication we present a study of the variation of the lattice parameters of several homoepitaxial InP layers grown by hydride vapour phase epitaxy (HVPE) under different stoichiometric conditions by using High Resolution Diffractometer (HRD). A single wafer has been used to obtain several substrates of size 10x10 mm² in area assuming that the wafer has the uniform behaviour. Deposition was carried out under several gas phase stoichiometric ratios keeping the other parameters constant. HRD has been used to detect both the variation of lattice parameter with reference to InP substrate and the full width at half maximum (FWHM) using (117) reflection. It has been noted that the high quality layers have the smallest lattice parameter, while other conditions (P-rich or In-rich) leads to lattice dilation. This seems to be in contrast with the expectation that an excess of smaller atoms (P in this case) will cause a contraction in the atomic bond; In general it is noted that the lattice parameter is high under off-stoichiometric conditions. This is considered as mainly due to the creation of antisite defects. Since our previous studies have shown that the stacking faults depend upon the growth conditions /3/ a possible relationship between the lattice parameters and defects will be presented.

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EVIDENCE FOR NONUNIFORM INTERFACE THICKNESS IN STRAINED GaInAs/InP QUANTUM WELLS

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Advanced materials for optoelectronic devices production increasingly use ultrathin (a few monolayers thickness) quantum wells (QWs) of InGaAs lattice matched to InP. For instance, in the particular case of optical fibers communications using 1.3 μm wavelength, the standard requirement is to growth active layers of about 8 monolayers (MLs) thickness, with abrupt interfaces and good uniformity accross a 2 inches wafer. In this case, in order to combine mass production techniques with a high degree of integration, Low-Pressure Metal-Organic Vapor Phase Epitaxy (LP-MOVPE) seems to be the most promising technique. However, because LP-MOVPE is very sensitive to the gas switching^[1] and growth interruption^[2,3] sequences, finite interface layers develop and modify the optical properties of the devices^[4]. In this work, we demonstrate that such interfaces are not uniform but, depending on the initial degree of coverage with foreign species, the typical dispersion, for a given series of samples, is of the order of 0.5 Langmuir.

We consider a series of strained GaInAs/InP multi-QWs, with nominal thicknesses 5 MLs and gallium compositions ranging from 0.17 to 1. From low temperature photoluminescence data (PL), large flat surfaces at the scale of the exciton Bohr radius can be demonstrated with distinct series of peaks corresponding to MLs well width fluctuations. The most important point is that, in order to account for the composition dependence of the PL lines, large (at least 4 MLs thick) interface layers of average composition InAs_{0.65}P_{0.35} are needed. Moreover, from the experimental data, it is clear the MLs fluctuations do not simply correspond with a change in thickness of the active layers (GaInAs) but also that changes in the width of the layer interface (InAsP) are involved.

We have used a Green function approach, combined with a transfert matrix method, to account for these experimental data. We start from the ideal square wells situation with structures made of 1, 2 or 3 MLs of InAs (lower interface) sandwiched between 5 MLs of GaInAs (nominal wells) and one InP barrier. Then we compute:

- i) the compositional change of chemical species (intermixing) induced by in-situ diffusion at growth temperature $T(g) = 650^\circ\text{C}$ during the growth sequence;
- ii) the resulting energy levels.

Without any adjustable parameter, we find clearly that, depending on the initial coverage assumed for the interfacial layer, the final perturbation (real interface thickness) changes. For instance, starting from 2 MLs of InAs, it will run to 5 MLs of (mainly) InAsP with average composition Ga₁In₉As₆P₄. Within this model, all experimental data can be satisfactorily accounted for assuming initial coverage between 1.5 and 2.5 Langmuir.

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A CONTROLLABLE MECHANISM OF FORMING EXTREMELY LOW RESISTANCE NONALLOYED CONTACTS TO GROUP III-V COMPOUND SEMICONDUCTORS

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The successful operation of modern microelectronic and photonic devices is determined to a large extent by the quality of ohmic contacts. The objective of this work is to establish the formation mechanism of low resistance nonalloyed Ti/Pt/Au ohmic contacts to p-GaAs, p(n)-InGaAs and n-InAs.

Experiments were performed using a variety of III-V layers of 0.5 μm thickness grown on semi-insulating substrates by molecular beam epitaxy or metalorganic vapour phase epitaxy. Different doping levels ($1 \cdot 10^{19}$ - $2 \cdot 10^{20} \text{ cm}^{-3}$) were employed in order to determine the minimum concentration which guarantees the tunneling behaviour of the ohmic contact. Test structures for contact resistivity measurements by means of the extended transmission line model were prepared. The fabrication technique includes an effective cleaning of the semiconductor surface by bombardment with low energy argon ions prior to the metal deposition. The induced defects were removed during very rapid thermal processing of the as-deposited contacts for only 1 s at temperatures ranging from 300 °C to 550 °C. For the Ti/Pt/Au contacts to both p-GaAs and p-InGaAs the optimal annealing temperatures were 450 °C and 400 °C, respectively. The same contacts to n-InAs and n-InGaAs exhibit ideal ohmic characteristics without any intentional annealing.

Extremely low resistances of $2.8 \cdot 10^{-8}$, $4.6 \cdot 10^{-8}$ and $1.7 \cdot 10^{-8} \Omega \text{ cm}^2$ were achieved for the contacts to p-GaAs ($2 \cdot 10^{20} \text{ cm}^{-3}$), p-InGaAs ($1 \cdot 10^{20} \text{ cm}^{-3}$) and n-InAs ($2 \cdot 10^{19} \text{ cm}^{-3}$), respectively. The specific contact resistance for GaAs is the lowest ever reported value for an ohmic contact to p-type III-V compound semiconductor.

For an analytical investigation of the contact morphology Rutherford backscattering spectroscopy (RBS) was applied. The distribution of the contact constituents was determined by RBS utilities and manipulation package (RUMP) simulations. The detailed studies make evident that within the resolution limit of the RBS no variation of the film composition occurs when the contact is sintered at optimal conditions. Thus, metallurgical reactions are not essential for obtaining low resistance contacts with an excellent homogeneity and uniformity. Heating the samples at temperatures higher than 500 °C leads to the formation of a complicated multilayer structure, where the Ti film acts as a collector for the outdiffused As.

The reliability of the used fabrication technique, its reproducibility and universality also will be discussed. High quality InGaAs/InGaAsP multiple-quantum-well ridge waveguide lasers with a low series resistance of $R_s = 4 \Omega$ (2 μm -wide ridge mesa) and buried ridge structure lasers with $R_s = 2.5 \Omega$ (5 μm -wide contact stripe) were fabricated with a superior reproducibility utilizing the described contact procedure.

The extremely low resistance contacts provide a useful tool for examining the role of other factors, e.g. reactive ion etching induced damage and non-uniformities at the isotype heterojunctions. The improvement of the ohmic contacts revealed a distinct kink-effect in the laser I-V plots. This effect appears as a result of the voltage decay at the p-InGaAs/p-InP junction due to thermionic current emission across the volume band spike. The kink-effect was not detectable previously when the fabricated ohmic contacts were far from being ideal.

MODIFICATION OF SEMICONDUCTOR-NATIVE OXIDE INTERFACES DURING OXIDATION OF SOME III-V SEMICONDUCTORS

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There is considerable interest to the low temperature techniques of synthesis insulation film on compound semiconductors as well as material properties characterization of the insulator-semiconductor interfaces.

In the present work we report the result of a study of photochemical and thermal oxidation of semiconductor (GaAs, InP et al) in O_2 , elemental and chemical composition of the native oxides and their interface with semiconductors by ellipsometry, x-ray photoelectron and Auger electron spectroscopies.

We have observed a strong enhancement of oxidation on III-V semiconductor surfaces using deep-UV photons (123.6, 147 and 184.9nm). A fairly high rate of GaAs oxidation has been able even at room temperature. Very efficient carbon contamination removal from the semiconductor surfaces has also observed after such treatments.

It is shown that the accumulation of elemental As at the GaAs-native oxide interface during GaAs oxidation depends on the temperature but not the rate of oxidation. In contrast, the enrichment of phosphorus compounds at the InP-native oxide interface during InP oxidation depends mainly on the rate of oxidation. A possible mechanisms of III-V semiconductor surfaces oxidation and of semiconductor-native oxide interfaces modification are discussed.

INVESTIGATIONS OF THE n-GaAs/ELECTROLYTE INTERFACE WITH TIME-RESOLVED PHOTOLUMINESCENCE

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The decay of band-to-band photoluminescence (PL) for n-GaAs (Te; n_0 : $5 \cdot 10^{17}$ and $1 \cdot 10^{18} \text{ cm}^{-3}$ respectively; (100) surface orientation) in contact with aqueous 1N HCl was investigated with both boxcar and time-correlated single photon counting technique for various excitation intensities and for various externally applied potentials. In the case of boxcar technique the excitation intensities could be varied between 1440 and 0.50 kW/cm^2 at a wavelength of 636 nm corresponding to an initial excess carrier concentration $\delta p(0)$ of $5.5 \cdot 10^{19} \dots 2 \cdot 10^{16} \text{ cm}^{-3}$. A (mono- or bi-) exponential least-square fit of the luminescence decay was used.

Keeping the electrode potential near to the point of zero photocurrent (-0.5 V/SCE) the following results were obtained: Starting from the lowest excitation intensity the part of the fast decay term of the biexponential fit increases significantly with excitation intensity. At high intensities the shape of the luminescence decay becomes nearly monoexponential (decay time $\tau \leq 1 \text{ ns}$). A new effect concerning the dependence of the decay time on the excitation intensity was found: There is a maximum of the monoexponential decay time in the range of linear recombination ($\delta p \leq n_0$) which steeply descends towards high intensities.

In the range of this maximum the influence of externally applied potential on the parameters of the biexponential decay was studied: Both decay times increase towards more cathodic potentials and the part of the slower decay process decreases relatively.

To interpret the experimental results we simulated PL-decay curves with linear and quadratic recombination model as well as with the program package TOSCA¹ (Two Dimensional Semiconductor Analysis Package) solving the equation system of Van Roosbroeck² numerically. TOSCA includes radiative, Schockley-Read-Hall, surface and Auger recombination as well as optical generation and photocurrent losses. The maximum found for the monoexponential decay time vs. excitation intensity can be reproduced and physically explained by the results of TOSCA.

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EVALUATION OF ZnSe and ZnTe MOVPE EPITAXIAL LAYERS
FROM PHOTOLUMINESCENCE AND CATHODOLUMINESCENCE STUDIES

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Recently it has been shown that high quality ZnSe, and ZnTe films can be grown on GaAs by low temperature growth techniques such as Metal Organic Chemical Vapor Deposition. Epitaxial layers of ZnSe and ZnTe were elaborated using the MOVPE at low pressure. We used triethylamine dimethylzinc as zinc organometallic precursor for growth of ZnSe, and ZnTe. The H_2Se hydride was used as Se precursor as usual. Characterization of the layers was carried out by Photoluminescence (PL), Cathodoluminescence (CL), and Secondary Electrons Scanning Microscopy. PL and CL exhibit the same features for the band edge as well as for the self activated levels : the band edge image of the layers is very contrasted contrary to the self-activated levels ones. Secondary electron cartography quite agrees with the CL ones. From both technics a rough estimation of the dislocation density is reported, indicating a high cristallographic quality of the layers.

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Characterization of ohmic contacts on n and p type GaSb

Gallium antimonide and its quaternary derivatives, such as GaInAsSb, are powerfull materials for photodetectors and solid state lasers operating in the 2 - 4 μm range. Associated with fluoride glasses they potentially allow the achievement of non dispersive long haul and high speed telecommunications. Both components need high performances ohmic contacts. We realized them with using Zn/Au multilayers for p-type GaSb and Te/Au multilayers for n-type GaSb. Contacts were electrically characterized by their specific resistance which could be obtained currently as low as $10^{-5} \Omega\text{cm}^2$ for p-type GaSb and $10^{-6} \Omega\text{cm}^2$ for n-type GaSb.

The contact morphology and composition are essential parameters to improve their quality. We studied the surface morphology and composition by means of SEM (Secondary and backscattered electrons) and SIMS. These last techniques allow to optimize the semiconductor surface preparation, the contact composition and the sample thermal treatment.

Such ohmic contacts allowed us to reduce the serie resistance of infrared laser diodes based on GaSb of more than one order of magnitude.

CHARACTERIZATION OF TANDEM AND POLYCRYSTALLINE GaAs DEVICES BY LIGHT BEAM INDUCED CURRENT MAPPING

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Structural defects and fabrication steps which can induce other defects are known to greatly impact device performance and lifetime in semiconductor technology. Consequently, the development of suitable devices needs the use of non destructive analytical techniques for the electrical characterization of the device performance. For this purpose, a high spatial resolution apparatus for precise analysis of local photovoltaic properties has been designed. It is the aim of this paper to show the performance of the Light Beam Induced Current (LBIC) mapping for controlling various stages during the fabrication of photovoltaic devices. Two types of devices were analysed: high efficiency multispectral tandem GaAs solar cell and new low cost solar cell made from polycrystalline GaAs substrate.

The LBIC experimental set up has been used for several applications (see e.g.[1]). A GaAs laser diode (780 nm) in a pulsed mode was the light beam source. The beam was focused by diffraction limited optics; the spot diameter and the depth of field of the incident beam were 6 μm and 100 μm respectively. A low power laser diode (150 μW) was used to avoid any changes in the local transport properties. The test-device was moved under the fixed laser beam on computer-controlled X,Y translation stages (resolution 1 μm). The numerical photocurrent value for each point was averaged in order to get a good signal / noise ratio and the associated value was transferred to the computer memory. After computer processing of the image, the local transport properties were displayed using grey levels or arbitrarily chosen colors. A two-dimensional topograph was obtained on the color display monitor by selecting i photocurrent intervals associated with i levels.

Multibandgap systems with two junctions of different energy gaps is a promising way to improve the efficiency of concentrating type photovoltaic devices [2]. A very efficient band gap combination is given by the GaAs - $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}$ couple. Such a device creates two stacked junctions which are electrically independent. The first junction was formed by two GaAs layers, Sn and Ge doped, grown by Liquid Phase Epitaxy (LPE) on a p^+ substrate. Then a Sn - doped $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}$ layer (about 10 μm thick) was fabricated. Finally, a thin graded AlGaAs window layer was deposited by isothermal LPE. During the contacting process, Be diffuses into the $\text{Al}_{0.32}\text{Ga}_{0.68}\text{As}$ layer to form the upper junction of the device.

The homogeneity of the local photocurrent was investigated by LBIC imaging. High resolution LBIC topography was typically generated using 400 lines with 400 points in each line. The 780 nm wavelength of the incident beam is well adapted to the present study since the window and the first junction are transparent to the light, thereby allowing a clear imaging of the second junction. The buried active junction is electrically imaged at 9 μm below the surface by this non destructive method.

On the other hand, in the case of polycrystalline GaAs substrate [3], the recombination properties at the grain boundaries can be analysed by LBIC mapping. The repartition of the measured photocurrent or photovoltage can be correlated with the different grains of the analysed zone. Details of our present results will be presented.

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**The Effect of Sampling Grid Density on Process Control Values
Derived from Spatially Resolved Photoluminescence Measurements**

by

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Recent work [1,2] has shown that room temperature spatially resolved photoluminescence (sRPL) can be used as a front end screening technique to predict optoelectronic device performance. However, development of a successful correlation requires very careful experimental planning and execution. This paper will discuss the practical aspects of the correlation of device performance with photoluminescence by examining the effects of the measurement methodology, spatial sampling statistics (i.e. sampling grid size) and spatial point density on typical process control variables such as the average peak wavelength, peak intensity, intensity at a single wavelength and full width of the peak at half maximum.

Results will be presented for a number of sample structures with particular emphasis on InGaAs(P) on InP epitaxial wafers grown by a number of industrial sources. The effect of varying the sampling grid density and orientation on the process control value of interest will be discussed and analyzed. The results of this data, in conjunction with other measurement criteria such as edge exclusion parameters, will be shown to have a large effect on the reproducibility of the measured PL value and hence the empirical correlation to device performance.

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Non-destructive, Whole Wafer Assessment of Optoelectronic Materials by Scanning Photoluminescence

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Since the fabrication of optoelectronic devices is a complex and expensive process it is highly desirable to characterize both starting material and epitaxial structures at any stage of technological process. The ideal candidate which meets the production and research criteria is scanning photoluminescence (sPL) technique [1-3].

In this paper we describe apparatus for measuring photoluminescence over the entire wafer and discuss specific examples related to qualification of substrates and compound epitaxial materials grown by LPE and MO VPE. The origin of PL contrast in different cases is discussed and some physics underlying photoluminescence process is given.

We also show how a combined use of non-contact surface photovoltage (SPV) technique and scanning photoluminescence (sPL) can contribute to our understanding of a variety of processing effects in both compound semiconductors and elementary silicon.

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DEPENDENCE OF SURFACE MORPHOLOGY AND DISLOCATION STRUCTURE
IN LATTICE MISMATCHED InGaAs/InP HETEROSTRUCTURES
INVESTIGATED BY AFM AND TEM

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The surface morphology of epitaxially grown semiconductors is of great importance as the performance of most electro-optical devices depends on the structural quality of their interfaces. This is particularly true for strained and totally relaxed lattice mismatched systems. In this work we use Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) to study the dependence of the surface morphology on the interfacial dislocation structure in partially relaxed lattice mismatched (LMM)InGaAs/lattice matched (LM)In_{0.53}Ga_{0.47}As/ InP systems.

First, the surface crosshatched morphology and the interfacial misfit dislocations were examined for In_{0.65}Ga_{0.35}As / LM InGaAs structures. The In_{0.65}Ga_{0.35}As layers which have a 1% lattice mismatch with the substrate were grown by molecular beam epitaxy at 525°C at thicknesses well above the critical thickness required for generation of dislocations. TEM results reveal an orthogonal network of 60° dislocations with lines lying in the heterointerface with an average spacing of 525 Å which indicates an incomplete relaxation (255 Å expected for full relaxation). AFM measurements show also a crosshatched morphology with a feature spacing of approximately 5000 Å and a depth of about 80 Å. These observations are explained both by the pile-up of surface steps resulting from the glide of 60° dislocations in (111) planes and by inhomogeneous lateral growth rates on partially relaxed materials.

Long isolated V-shaped grooves are observed by SEM and AFM on the surface of highly strained LM InGaAs / In_{0.82}Ga_{0.18}As / LM InGaAs quantum well structures. Such surface morphological defects imply inhomogeneous local growth rates. Their origin seems to be directly related to the existence of isolated dislocations (observed by TEM) appearing at the In_{0.82}Ga_{0.18}As / LM InGaAs interface during the growth of the strained ($\epsilon=2\%$) In_{0.82}Ga_{0.18}As layers. Isolated misfit dislocations can induce a local relaxation along long lines in the [1-10] azimuth. It is believed that when strained and relaxed areas coexist in the In_{0.82}Ga_{0.18}As layers the epitaxial growth of LM InGaAs is favored on strained lattice matched areas. The large surface mobility of group III species allows the system to move towards a more stable state which lead to lateral thickness variations as large as 50% at the vicinity of relaxed regions.

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Stress relaxation in the buffer layers of (Cd,Zn)Te heterostructures

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We report a series of optical investigations performed on three CdTe/(Cd,Zn)Te strained quantum wells (SQWs) and two superlattices (SLSs) grown by molecular beam epitaxy (MBE) on $\text{Cd}_{0.96}\text{Zn}_{0.04}\text{Te}$ substrates. Depending on the structure, two different types of buffer layers have been used :

- i) for the three SQWs, (Cd,Zn)Te alloys with Zn composition (around 15 %) identical to the one of the barrier ;
- ii) for the two SLSs, pure CdTe.

From piezoreflectance measurements combined with first-order derivative of the reflectivity, we identify (in terms of heavy- and light-hole excitons) all excitonic features associated with the optically active layers (substrate, buffer layer, SQW or SLS). From the analysis of the optical transitions originating from the buffer layer, we do not find a simple light hole-heavy hole splitting (like one is used to find in strained layer) but a multiple and more complexe structure. Comparing the experimental and theoretical energy positions deduced from electronic calculations, this evidences a step-like behavior of the stress relaxation in the buffer layers.

Finally, concerning the SLSs, we show that the residual internal strain which lies inside the buffer layers lifts the [001] axial symmetry of the structure. This seems to come from the anisotropy of the strain relieving dislocations and is still under investigation.

**Electronic structure of (Ga,In)As-(Ga,Al)As
strained-layer quantum wells grown on relaxed buffer layers**

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We discuss the design and growth of relaxed buffer layers, where the objective is to achieve a single crystal, defect-free surface with a lattice constant different from that of the substrate. From experimental photoluminescence data in the (Ga,In)As system, we suggest that the in-plane constant should be changed in small steps, and that before each change in lattice constant, the residual stress should be balanced by tensile stress so that the buffer layer is free from external stress. The influence of such built-in strain on the full electronic structure of strained-layer quantum wells has been calculated by including contribution of excited bands into a sophisticated version of the envelope function approach. To compare the predictions of this model with experimental data, we grew a series of (Ga,In)As-(Ga,Al)As single quantum wells where both built-in strain effects and potential wells were appropriately varied to quantify the effect. Reflectivity data taken at 2K, where we could measure ground state type I as well as excited type I and type II transitions have revealed that a correct description of these heterostructures requires to include the influence of the spin-orbit split-off states in the valence band physics as soon as the configuration of the electron to light-hole potential profiles switch from type II to type I. We anticipate that this effect should be included for the calculation of threshold currents in quantum well lasers made from such heterostructures.

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Characterisation of the crystallographic defect structure in selected area epitaxial growth of GaInAs on InP by metalorganic chemical vapour deposition

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Selected area epitaxy (SAE) is an important technology in the development of optoelectronic integrated circuits. In this paper we describe the crystallographic structure of SAE overgrowths by metalorganic chemical vapour deposition (MOCVD) of InP and GaInAs on partially masked (100) InP substrates using energy dispersive X-ray analysis, transmission electron microscopy (TEM) and high resolution electron microscopy (HREM). The presence of the oxide mask which specifies the selected areas for epitaxial deposition has the effect of perturbing the gas flow over the surface of the substrate, which can modify the local composition of the depositing material and result in the incorporation of interfacial misfit stresses. This modification can have significant deleterious effects on the crystallographic and electronic properties of the material.

Fig 1 is a cross sectional view of the edge of one such epitaxial region, where the mask edge is parallel to the [011] substrate orientation. A region of SAE material is observed of excess thickness adjacent to the mask edge, having a very high density of defects. In the region of excess thickness, the overgrowth is non-planar and faceted on {111} and {001} planes. A (100) planar surface is reestablished at a distance of several micrometres from the oxide edge. Furthermore, we identify an array of dislocations at the GaInAs/InP interface extending from the mask edge towards the centre of the epitaxial region. A greater propensity for the formation of these

dislocations is observed when the mask edges are aligned to $[0\bar{1}1]$ as opposed to [011]. For other mask orientations, such as those intermediate to the orthogonal $\langle 011 \rangle$ directions, we observe roughly similar crystallographic defect structures. Fig 2 is a plan view micrograph of the edge of an epitaxial window with the mask edge aligned to [010]. An orthogonal grid of 60° dislocations having $\langle 110 \rangle$ line vectors occurs in unmasked epitaxial regions, which we believe lie at the GaInAs/InP buried interface. These dislocations are able to relieve elastic misfit stresses between the GaInAs and InP layers. We relate the occurrence of these misfit dislocations to the chemical inhomogeneities present in the SAE regions as a result of the perturbations due to the presence of the mask. HREM allows us to identify a variety of different misfit relieving defects, the type and generation of which is influenced by the crystallographic orientation of the strain modulation in the non-planar overgrown regions.

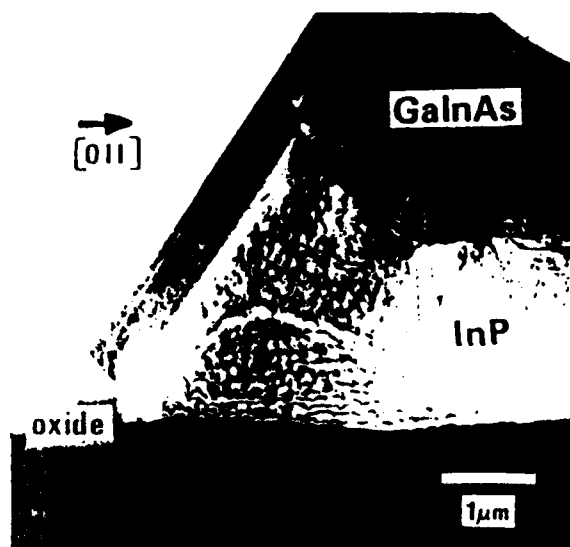


Fig 1 (0 2 2) dark field TEM micrograph of the edge of a [011] aligned oxide mask on InP.

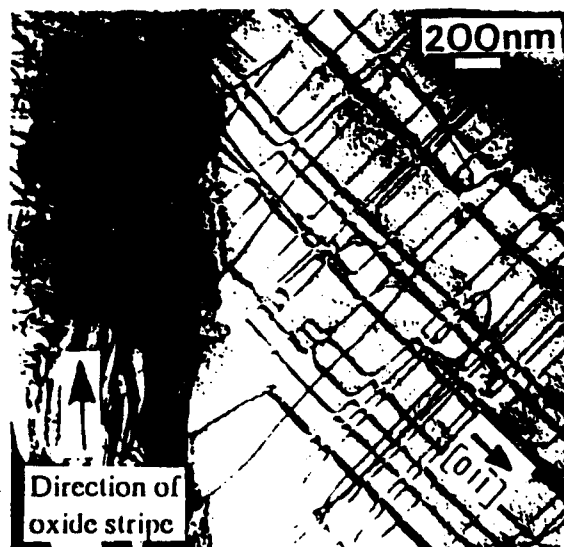


Fig 2 (0 2 2) dark field TEM micrograph of SAE growth adjacent to a [010] oriented mask edge.

Raman investigation of the photocarrier properties in both undoped and Fe-doped InP substrates

by

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Apart from the fact that InP and its related alloy epilayers have interesting properties in the areas of high-speed circuitry, integrated optoelectronics and high-power devices, InP solar cells experience increasing interest as a promising alternative in space applications. However, InP-based cells have not yet reached performances and long-term reliability as compared to similar Si or GaAs-based devices due in part to the specific properties of InP surfaces or interfaces. In this context, we have studied the recombination kinetics of optically excited electron-hole pairs generated in the continuous regime in both nominally undoped and Fe-doped InP substrates using Raman scattering from the longitudinal optical phonon-plasmon coupled mode L^+ .

Quite different results have been observed according to whether the material was Fe-doped or not. While undoped samples showed a pronounced coupling effect, Fe-doped specimens did not evidenced such a behavior. From model analysis, it is demonstrated that undoped (n-type) InP is characterized by a rather low surface recombination velocity ($S < 10^4 \text{ cm s}^{-1}$) and a (bulk) pair lifetime τ of the order of 50 to $100 \times 10^{-9} \text{ s}$. On the other hand, in Fe-doped (semi-insulating) InP, the photoexcited carrier density is found to depend strongly on the atomic Fe concentration with a critical value around 10^{16} cm^{-3} , whereas the photocreated pair lifetime is estimated to be lower than 10^{-9} s . Comparisons are made with published photoluminescence results obtained with similar substrates.

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PHOTO-EPR OF THE ANION ANTISITE IN InP

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Anion-antisite-related defects in III-V semiconductors have become a subject of intensive research over recent years since they appear to be the most typical intrinsic defects in these binary compounds.

In contrast to GaAs, where the As_{Ga} antisite is already observable in as-grown materials by conventional Electron Paramagnetic Resonance (EPR) techniques, the P_{In} antisite in InP has only been revealed after electron or neutron irradiation.

On account of the close analogy between neutron irradiation and ion implantation regarding associated lattice damage, we investigated neutron-irradiated undoped InP by photo-EPR using both intrinsic and extrinsic illuminations.

At 4.2 K, photoexcitation of the irradiated InP samples enhances the P_{In} EPR signal whatever the photon energy used. However this additional contribution subsequent to illumination rapidly decays for photons of below band gap energy ($h\nu \leq 1.05$ eV), whereas it persists for light of near or above the bandgap energy ($h\nu \geq 1.38$ eV) as long as the sample is kept at low temperature. This persistent contribution is quenched after heating the samples above 120 K.

These results may be explained in terms of different electron trapping mechanisms related to the different photon energies.

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EFFECTIVE n-TYPE DOPING OF InP BY THE NEUTRON TRANSMUTATION TECHNIQUE

by

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Many electronic devices, especially those operating at high voltages and currents like, e.g., avalanche photodiodes, power transistors and thyristors require substrates doped with high uniformity in order to withstand conditions of extreme operation. In this context, the Neutron Transmutation Doping (NTD) technique is a convenient method for introducing dopant impurities in a semiconducting material with the two main advantages of controllability and uniformity.

In the case of InP, NTD is expected to be particularly effective for obtaining n-type material owing to the large neutron capture cross-section of the ^{115}In nuclei ($\sigma_c = 199\text{ b}$) and to the natural abundance (95.7%) of this isotope. Further, ^{115}In transmutes basically into stable ^{116}Sn which is a potential n-type dopant in InP. However, (n, γ) induced defects by β^- recoils or γ -ray emission impose a post-irradiation annealing step to obtain the expected electrical activity.

Unintentionally doped InP substrates have been irradiated with thermal neutrons to obtain Sn-doping levels in the $10^{17} - 10^{18}\text{ cm}^{-3}$ concentration range and then rapidly annealed ($550^\circ\text{C}/10\text{s}$) using the proximity configuration. The samples have been characterized both by Hall effect and Raman spectroscopy to gather electrical as well as structural informations.

From a quantitative analysis of the Raman data, it is observed that after irradiation, initially n-type samples present a semi-insulating character, and that defects introduced during transmutation are mostly limited to point defects. After annealing, carrier concentrations measured by Hall effect are found to be in good agreement with predicted values, whereas those deduced from the Raman coupled-mode analysis are systematically lower by $\approx 30\%$. This suggests that unannealed defects are still present in the near-surface region of the substrate.

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Characterization of the homogeneity of semiinsulating
InP and GaAs by spatially resolved photocurrent.

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Photoconductivity has been proven to be a suitable technique for the characterization of semiinsulating GaAs and InP. It provides useful information on deep levels as EL2 in GaAs and iron in InP. These defects are known to be non-uniformly distributed at both the short and long range scale. We present herein an experimental set up that allows to study the bulk non homogeneities through the photocurrent contrast. The excitation is made with a YAG laser through microscope optics, which allows a high spatial resolution. Undoped LEC GaAs and Fe doped InP were studied. The study of GaAs was devoted to the spatial distribution of two slow relaxation phenomena typical of this material, namely the Photoquenching (PQ) and the Enhanced Photocurrent (EPC). The photocurrent variations in InP:Fe are related to the inhomogeneous distribution of neutral iron atoms Fe^{3+} . This non-uniformity was studied at both short and long ranges, showing good agreement with other results reported in the literature, relative to the nonhomogeneity of this material.

Raman characterization of GaAs doped with tin by laser assisted diffusion

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Heavily doped GaAs samples were prepared by laser assisted diffusion of tin. Carrier concentrations as high as 10^{19} cm^{-3} were reached by this doping procedure. Raman Spectroscopy was used to characterize the doped layers. This study was made as a function of the laser energy density used for tin diffusion, which ranged from 0.3 J/cm^2 to 0.7 J/cm^2 . An in depth analysis was also carried out by rastering with a Raman microprobe ($\sim 1 \mu\text{m}$ spatial resolution) a beveled surface (angle 17°). The Raman spectra of these samples are characterized by two peaks, an LO-like and a TO-like Raman bands, which the origin is discussed in terms of dopant activation and damage induced by the process of laser diffusion. The coupling of LO-phonons and plasmons and the breakdown of the momentum conservation rule are analyzed as the mechanisms giving the observed Raman spectra. The results are compared with the data obtained using other experimental techniques (SIMS, PCIV, Hall)

In-line Control of the Fabrication of Lattice Mismatched Photodiodes by Integrated and Spectrally Resolved Scanning Photoluminescence

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Lattice mismatched InGaAs/InP heterostructures are good candidates for the realization of optoelectronic devices with extended spectral response up to 2.5 μ m. The experiments reported here were carried out during the fabrication of photosensitive elements for IR cameras destined for the satellite SPOT 4.

Linear arrays of p-i-n photodiodes were realized by planar technology, using Zn diffusion into InP/InGaAs/InP heterostructures grown by MOCVD. The In content in the ternary layer was about 60%. The dimensions of the elementary photodiode cells are 24 μ m x 48 μ m.

The lattice misfit was determined by X-ray diffraction and the bandgap of the InGaAs layer was measured with spectrally resolved photoluminescence and IR transmission. Integrated and spectrally resolved scanning photoluminescence (SPL) measurements were carried out at successive steps in the process : substrate preparation, epitaxy, insulator deposition, annealing, photolithography and Zn diffusion. Electrical and photo-electrical characterization was carried out on the completed devices.

In this presentation we will show and discuss the following results and developments :

- procedures for routine control of the spectral uniformity of epitaxial layers (extraction of the spatial distribution of the peak position, full width at half maximum (FWHM), center wavelength at half maximum and amplitude of the photoluminescence bands), statistical treatments of these parameters ;
- correlation between the presence of dislocations in InGaAs layers detected by high resolution (1 μ m) SPL and the dark current of individual photodiodes ;
- procedures for SPL measurements and data treatment (after successive steps in the process) which allow the prediction of the performances and the fabrication yield of the photodiodes ;
- survey of the uniformity of processed wafers with histograms of the PL distribution ;
- reproducibility control of independent runs with sets of histograms (obtained after successive steps) which we consider as "identity cards" of the process.

IMPROVEMENT IN THE DEEP LEVEL TRANSIENT SPECTROSCOPY ANALYSIS OF DEFECT LEVELS

by

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During last years, Deep Level Transient Spectroscopy (DLTS) has been improved by reducing the time of the measurement and the energy resolution. In spite of these progress, the difficulty of analysis remains. This is particularly the case for InP for which a lack of knowledge of the characteristics of the defects is evident related to the large dispersion of bulk properties of available substrates.

We have analysed Au-InP interface by DLTS. The spectra show particular peaks configuration. The peaks cannot originate from single discrete levels, many bulk levels or interface states may be involved. Non ideal experimental conditions for the capacitance measurements or overlapping spectra due to closely spaced levels can lead to serious errors in the interpretation.

We have used several correlation techniques in order to improve the energy resolution. The three point method [1] which gives a value of $1.78kT$ has been successfully carried out. The signal to noise ratio is also improved with a special smoothing procedure of the capacitance transients and of the DLTS signal. With the three point and the two point method we have been able to separate peaks coming from bulk levels that classical boxcar or lock-in measurement systems cannot distinguish.

We have also developed a new method to analyse DLTS spectra. This method give us more information about the spectra than the Lang's analysis. Instead of taking only the point corresponding to the maximum, we use complementary points on each side of the peak in order to plot the Arrhenius curve. In this way, we can clearly show the appearance of overlapping levels on one side of the peak.

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NON-DESTRUCTIVE MAPPING OF SEMICONDUCTING LAYERS
USING A MICROWAVE DEVICE.

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We propose a novel non-destructive method which allows to determine the sheet resistance (R_{\square}), the mobility (μ) and the density (n) of the free carriers of semiconducting layers. Superficial or buried layers can be measured. The sample may be of any shape and in particular, this method is useful to characterize wafers. The measurement cell [1-2] consists of two microstip lines on flexible Duroid substrate. The ends of these lines are covered with a thin insulator layer and act as electrodes. To characterize a sample, the electrodes are only pressed on it and a measurement of the modulus of the transmission factor S_{ij} between the two lines is performed. Eliminating the scattering factor phase leads to a simplification of the experimental set up and a lowering of its cost. At the working frequency (1-2 GHz) the impedances values of the capacitive contacts are small with respect to R_{\square} . So, the resistance between the two electrodes is easily obtained and R_{\square} from it. The determination of μ results from magnetoresistance measurements. Then, the value of n can be calculated if the thickness of the layer is known. The measurement ranges are as follows:

$$100 \, \Omega < R_{\square} < 3 \, \text{k}\Omega$$

$$2000 \, \text{cm}^2/\text{V.s} < \mu$$

The accuracy of the results achieved from our method or the van der PAUW one is similar. Lastly, the measurement system is controlled by a microcomputer, thereby the R_{\square} , μ and n mapping of a 2" wafer takes about 90 minutes for 40 sites (each site corresponds to a tested area of about $5 \times 5 \, \text{mm}^2$).

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Evaluation of MBE Grown GaAlAs/GaAs and AlAs/GaAs Multilayered Structures

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The control of the properties of the new generation of electronic and optoelectronic devices that exploit the quantum mechanical physics, such as high electron mobility transistors, quantum well lasers, Bragg reflectors, is achieved by the confinement or modulation of the charge carrier wavefunctions in potential wells. This is obtained by the formation of multilayered structures (superlattices and multi-quantum wells) which have heterointerfaces that must be as flat as possible so as to optimize parallel conduction and minimize carrier scattering in the wells. Also, the size of the wells affect the density of states and the spectral width of the emitted light. Typical materials used to fabricate such devices are AlGaAs, GaAs and AlAs. GaAs/AlAs superlattices (SLs) also serve as buffer layers as they prevent the propagation of both impurities [1] and dislocations from the substrate.

We report here on the use of transmission electron microscopy (TEM), on cross-section specimens, and double crystal X-ray diffractometry (DCD) to evaluate AlGaAs/GaAs and AlAs/GaAs SLs grown by MBE. The growth temperature was 610 °C and growth interruption at the interfaces was introduced to reduce interface roughness. Direct measurement of the width of the wells was carried out by the use of pictures taken in the (002) dark field and high (atomic) resolution modes of the TEM as well as by the evaluation of the satellite spots around the Bragg spots in electron diffraction. Only small deviation (~5%) with respect to the widths expected from the growth rate was found. Reasonable agreement was also found with the width determined by DCD by a simulation of the experimental rocking curves. In particular, for the $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ SL, by using the wells width evaluated by TEM, DCD simulations confirmed the expected x composition. Very thin SLs, e. g. ten couples of AlAs (1 nm)/GaAs (1 nm) could be measured only by TEM as their diffracting volume was too small to be detected by DCD. The roughness of the interface was checked by high resolution electron microscopy (HREM). The interface between the GaAs and AlGaAs layers, 7.5 and 9.8 nm wide respectively, had steps not higher than three atomic layers, irrespective of whether it was normal or inverted, thus confirming the effectiveness of the growth interruption procedure. Atomic steps, one monolayer high, were also detected in the AlAs (1 nm)/GaAs (1 nm) SL under particular TEM defocus values. Whether these steps are real or due to imaging conditions is still under study as the interpretation of the [110] HREM images for the AlAs/GaAs interface is not as obvious as for the AlGaAs/GaAs one.

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THE BULK AND SURFACE STATES OF GaSb-AlSb-InAs SUPERLATTICE

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ABSTRACT

The properties of semiconductor superlattices have been widely investigated, and studies have mainly considered dual-constituent systems.

In this work, electronic properties of the 3-layer semiconductor superlattice, namely GaSb-AlSb-InAs, will be presented.

This is an interesting heterostructure because the introduction of a third constituent (AlSb) in a GaSb-InAs superlattice may lead to new possibilities for device applications. This third constituent produces potential barriers for electrons and holes.

We examine the bulk and surface allowed states and their evolution with layer thickness. Depending on the choice of the material ending the superlattice (surface layer) and on the chemical nature (anion or cation) of the top plane, we may predict the occurrence of an accumulation region near the surface layer which keeps a bi-dimensional character. The position of the localized surface states associated with different surface configurations is examined in function of :

- i) The chemical nature of the surface layer .
- ii) The position of the bulk-material bands with respect to the superlattice sub-bands.

The main results concern the semiconductor - semimetal transition at a critical layer thickness and the behavior of surface states in the semi-metallic regime.

Title : CONTRIBUTION TO ANALYSIS OF PHOTOLUMINESCENCE
INTENSITY

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The characterization by luminescence response of SC wafers or more elaborate SC devices is now currently used. The use of focalized laser beam coupled to motorized translation systems gives mapping view of the intensity variations. The resulting luminescence image gives a lot of information about inhomogeneities of the investigated wafer. Thus defects, as doping variations, surface pollutions..... are detected by this technique. The sensitivity of this outstanding method places among the promizing non-destructive characterization methods. However the understanding of the luminescence contrast can be a limit factor for the interpretation of imaging. Models are suitable for this purpose. In this contribution we present a one-dimensional simulations of the intensity variations created by modification of surface recombination velocity on the one hand and by the modification of the space charge layers on the other hand. The combination of this two factors will give the variation scale of the luminescence contrast. Influence of factors as wavelength of the incident beam, doping level, diffusion length of minority carriers are investigated.

EBIC Characterization of LEC GaAs

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Since a long time EBIC (electron beam induced current) has been used to characterize semiconductors and electronic devices prepared from them. Such characterization relies on the dependence of the EBIC signal on a fundamental semiconductor parameter, i.e. the minority carrier diffusion length. EBIC has, therefore, been employed to determine the minority carrier lifetime and the electrical activity of the crystal defects as it has been shown that their dangling bonds as well as the impurities getterred by such defects locally reduce the minority carrier lifetime.

The EBIC signal, however, also depends on the width of the depletion region associated with the Schottky or p-n junction, fabricated in the semiconductor in order to carry out the EBIC experiment, and a method to extract such width has been suggested by the present author some time ago. Such width is a majority carriers property as it depends on their density. Results obtained by this method in the study of bulk GaAs are shown. In particular, it has been established that the dopant atoms play a major role in the formation of large impurity atmospheres around dislocations in Si-doped LEC GaAs giving rise to point defect reactions that might further explain the formation of the EL2 deep trap in these atmospheres. Additionally, it has been seen by EBIC that a short range ($< \sim 1 \mu\text{m}$), highly recombinative atmosphere forms close to the dislocations whereas at higher distances the dopant atmosphere is less recombinative very likely because of a smaller recombination efficiency and density of the impurities getterred there. Such short and long-range atmospheres around the same dislocation might be due to the electrostatic and elastic interaction, respectively, between impurities and dislocation. As a by-product of these results, a conclusive explanation of the so-called 'dot-and halo' feature around dislocations, detectable by both EBIC and cathodoluminescence, has also been given. Simultaneous measurements of the minority carrier diffusion length and majority carrier density have shown, in fact, that the bright halos are mostly due to a depletion of dopant atoms rather than of deep impurities.

By this EBIC method the determination of the dopant concentration at growth striations can be easily and directly carried out in GaAs as well as in any other bulk III-V compound despite the fact that they have a low diffusion length that prevents the use of former EBIC methods based on the measurement of the diffusion length. By this means the calibration of the etching rate as a function of the dopant concentration for the DSL photoetching has been made.

NON-DESTRUCTIVE CHARACTERIZATION OF BULK DISTRIBUTION OF ELECTRO-PHYSICAL PROPERTIES IN SEMICONDUCTOR STRUCTURES

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In this paper we consider the problem of non-destructive investigation of multilayer semiconductor structures by using of various techniques of scanning electron microscopy.

The first part of the work deals with the problem of the determination of the bulk distribution of the diffusion length by EBIC measurements and following special procedure of signal processing. In order to find the bulk distribution of the diffusion length it is necessary to have a number of signals obtained under different conditions of the experiment because the unknown function depends on more variables than the single signal does. In other words it is necessary to introduce an additional parameter as one more variable, which the signal depends on. Electron beam energy is usually used as a such parameter. Another way is to vary the depletion region width by means of the change of the applied voltage. We consider both approaches.

In the second part we consider the problem of the determination of bulk distribution of the atomic number by using of secondary and backscattered electron signals (SE and BSE respectively). The process of these signals formation is investigated. It is shown that the signal formation area consists of two parts: a narrow zone penetrating into the sample to a depth $\sim E$, where E is the beam energy, and a wide diffusion zone of scattering, and that the micro-inhomogeneity signal is mainly formed in the first zone. The width of the narrow zone at depth h equals to $(h^3/E^2)^{1/2}$ and, what is very important, it decreases if the electron beam energy increases. This leads to the possibility of getting of a high resolution, up to the width of the initial electron beam. It is also shown that secondary electrons take some information about deep layers from backscattered electrons which generate them and that this information is enough for observation of inhomogeneities on large depths. Moreover, the quality of SE images can be even better than those of BSE. The reason of this phenomenon is discussed in the paper. The above arguments are illustrated by a number of experimental results and also by Monte Carlo simulation.

INVESTIGATION OF GaSb SUBSTRATES BY SCANNING PHOTOLUMINESCENCE

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The GaSb related compounds are of increasing interest for optoelectronics devices like longwavelength lasers or photodetectors. The quality of the initial substrate is proving of great importance, as also its homogeneity. In this work, the scanning photoluminescence technique (SPL) is applied as a qualification test to GaSb substrates, as previously done for others III-V [1,2].

Two different ingots are studied. They have been Czochralski grown, in the $\langle 001 \rangle$ axis, in a similar way, with a growth rate of 2.5 cm by hour. The first one is n-type, Te doped, with a concentration of some 10^{17} cm^{-3} while the second one is p-type, non intentionally doped. A first set of samples has been cut in a (010) plane parallel to the $\langle 001 \rangle$ growing direction, and another one in the perpendicular plane. The SPL measurements are made at room temperature, the detection is performed via an InAs diode. Spatial inhomogeneities are found all along the growth axis, in the shape of large striations of about 1mm width, especially in the lead part of the ingot. The transition time was found to be an important parameter for the measurements and was non uniform all along the growth axis. The PL intensity increases from the lead to the tail part of the ingot. As expected a lower PL intensity was measured for the p-type crystal. Spectral measurements were also performed all along the growth axis. The PL principal peak much varies and is centered around 1730nm at the lead and at less than 1700nm at the tail part. The variations were of less importance for the p-type crystal. On a sample itself the variations are in the range of 5nm.

Moreover the gallium antimonide surface shows a high sensitivity when annealed, even at low temperatures[3,4]. Results are reported about the PL response of the surface of GaSb samples with annealing from 200°C to 650°C using the rapid thermal technique. For example the integrated SPL intensity for an n-type GaSb sample decreases by a factor ten for a 500°C annealing. In order to check the crystalline quality, some complementary results, obtained on the same samples by the Rutherford backscattering technique will be given.

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